MONTHLY NOTICES

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ROYAL ASTRONOMICAL SOCIETY

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OF THE PROCEEDINGS OF THE SOCIETY

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ROYAL ASTRONOMICAL SOCIETY

Vol. 108 No. 1

MEETING OF 1948 JANUARY 9

Professor W. M. H. Greaves, President, in the Chair

The election by the Council of the following Fellows was duly confirmed:—

Charles Richard Peter Allix, British Horological Institute, 35 Northampton Square, London, E.C. 1 (proposed by Sir H. Spencer Jones);

Francis Bolam Cohen, British Horological Institute, 35 Northampton Square, London, E.C. 1 (proposed by Sir H. Spencer Jones);

John Theodore Foxell, 128 Abbey Foregate, Shrewsbury, Shropshire (proposed by Dr L. J. Comrie);

Thomas F. Gaskell, Anglo-Iranian Oil Company, Britannic House, Finsbury Circus, London, E.C. 2 (proposed by Professor E. C. Bullard);

Kenneth Pritchard Harrison, King's College, Cambridge (proposed by Dr A. D. Thackeray);

Louis G. Henyey, Berkeley Astronomical Department, University of California, California, U.S.A. (proposed by S. Chandrasekhar);

Rudolph Luss, 87 Shlomo Hamelech Street, Tel Aviv, Palestine (proposed by Dr J. G. Porter);

Michael William Richey, 68 Cadogan Square, London, S.W. 1 (proposed by G. C. L Saul);

John Noel Taylor, 56 Arragon Gardens, Streatham, London, S.W. 16 (proposed by O. M. Watts); and

Francis Harry Thornton, Grove Mount, Davenham, Northwich, Cheshire (proposed by F. J. Hargreaves).

Fifty-five presents were announced as having been received since the last meeting, including:—

Angus Armitage, *Sun, Stand thou still* (presented by the author);

F. Becker, *Geschichte der Astronomie* (presented by the author);

Edmund Halley, *A Synopsis of the Astronomy of Comets* (presented by Sir Francis McClean); and

B.D. Charts (presented by Professor F. Becker).

The President announced that the Council had awarded the Gold Medal of the Society to Professor Bertil Lindblad of the Saltsjöbaden Observatory, Stockholm, for his work on the rotation of the galaxy, on the dynamics of stellar systems and on stellar luminosities. He announced also that Professor Lindblad had been invited to give the George Darwin Lecture for 1948.

The President announced that 1948 January 9 marked the centenary of the death of Miss Caroline Herschel. She had been elected an Honorary Member of the Society in 1835 February, together with Miss Mary Somerville.

The President announced that the Council had considered the possibility of providing facilities for Fellows resident outside the London area to attend meetings. The Council had therefore decided that one meeting per year, in addition to the normal meetings of the Society, be held outside London. The first of these meetings would be held in Edinburgh on 1948 October 29.

ANNIVERSARY MEETING OF 1948 FEBRUARY 14

Professor W. M. H. Greaves, President, in the Chair

The election by the Council of the following Fellows was duly confirmed:—

Gerald Balmforth, Commercial Arcade, Guernsey, Channel Islands (proposed by W. Kilshaw);

Donald Archibald Campbell, Alfarda, Lybury Lane, Redbourn, Hertfordshire (proposed by J. P. M. Prentice);

The Rt. Hon. Lord Cooper, 11 Parliament Square, Edinburgh (proposed by Professor W. M. H. Greaves);

Martin Ryle, Cavendish Laboratory, Cambridge (proposed by Dr A. D. Thackeray);

Edward Denton Sherlock, 11 Ballbrooke Avenue, Didsbury, Manchester 20 (proposed by H. L. Dilks); and

Sydney Ernest Williams, The University, Perth, Western Australia (proposed by Dr R. v. d. R. Woolley).

Sixty-nine presents were announced as having been received since the last meeting, including:—

Edward Ford, *David Rittenhouse, Astronomer and Patriot*, 1732–1796 (presented by A. Armitage); and

N. V. E. Nordenmark, *Pehr Wilhelm Wargentin*, 1749–1783 (presented by A. Armitage).

The President announced that Professor Bertil Lindblad, Gold Medallist for 1948, would deliver the George Darwin Lecture at the Ordinary Meeting on 1948 April 9 on "The Dynamics of the Stellar Systems".

The President then delivered his address on "The Photometry of the Continuous Spectrum". (See p. 131).

1948 FEBRUARY 14
ANNUAL GENERAL MEETING

Professor W. M. H. Greaves, President, in the Chair

The Minutes of the preceding Annual General Meeting were read, confirmed and signed.

The Minutes of the Special General Meeting of 1947 December 12 were read, confirmed and signed.

The President having appointed the Scrutineers, the Society proceeded to the ballot for Officers and Council for the ensuing year.

The Secretary read extracts from the Narrative Report of the Council.

The Report of the Honorary Auditors was read (see p. 14).

The Treasurer gave a brief explanation of the accounts and a survey of the Society's financial position.

A vote of thanks to the Honorary Auditors of the Treasurer's Accounts for 1947 was proposed and carried unanimously.

It was proposed and carried that the Report of the Council be received and adopted, and that it be printed and circulated in the usual manner, together with the Report of the Honorary Auditors and the President's Address.

The Scrutineers reported to the President the result of the ballot, and the names of the Officers and Council elected for the ensuing year were read to the Meeting. (The list of names is given on p. 152).

The thanks of the Society were given to the retiring Vice-Presidents (Miss M. G. Adam, and Mr D. H. Sadler) and other retiring members of the Council.

The thanks of the Meeting were given to the Scrutineers of the ballot.

The Meeting then adjourned.

REPORT OF THE COUNCIL TO THE HUNDRED AND TWENTY-EIGHTH ANNUAL GENERAL MEETING OF THE SOCIETY

1. *General.*—Under the conditions which have prevailed since the end of the war, the task of restoring and maintaining the normal services of the Society to its Fellows has been beset with many unexpected difficulties. This task has necessarily continued to absorb a great deal of the energies of the Council and of its Officers and Committees. Nevertheless, the Council has earnestly sought to look beyond just the restoration of former activities and to discern a pattern of further development of the Society's activities designed to enable it as vigorously as possible to advance its objects under the condition of the times. The part played by the Society in seeking provision for the creation of the Isaac Newton Observatory, as recorded in last year's Report, may be placed in this category. While less spectacular in character, the Council has this year to record under the same general heading the institution of Junior Membership, its plans for holding some meetings of the Society in places other than London, and certain special provisions for the production of *Occasional Notes*.

The Council hopes that the institution of Junior Membership will, to the advantage both of the individuals concerned and of the Society, encourage those who would normally join the Society to do so at an earlier age than they otherwise might and also attract a considerable number of those who would not otherwise consider the possibility of associating themselves with the Society. In this latter connection the Council is convinced that there are many young scientists who, though by no means all intending to devote themselves mainly to work in astronomy and related subjects, are deeply interested in current developments in astronomy and would welcome the opportunities for first-hand contact with these developments afforded by the Society's meetings, publications and library facilities. These are the opportunities which Junior Membership offers to such persons without involving them in the full obligations of Fellowship. The Council feels itself justified in supposing, however, that when they have had experience of the Society's activities a large proportion of them will desire to continue to share in these activities by becoming Fellows. They will be offered certain concessions in doing so. The Council hopes that these provisions will mitigate the effects of the increased annual contributions of Fellows which it has been compelled to ask the Society to sanction.

Last year's Report contained the sentence "Although relatively few Fellows are able regularly to attend meetings of the Society, they are the very essence of a corporate body and it is the Council's earnest endeavour to encourage Fellows to attend whenever possible". The Council's endeavour is now being directed to providing some opportunity of attendance at a meeting to those Fellows who live too far away to come to London for the purpose. It has resolved that from time to time meetings of the Society should be arranged at other centres of population in the United Kingdom. They are to be meetings of the Society

in the full sense, and not merely meetings held under its auspices. It is planned to hold the first such meeting in Edinburgh on 1948 October 29, the date having been selected in consultation with the appropriate authorities in Edinburgh to suit the convenience of those likely to attend. The proposal has met with an enthusiastic response from interested bodies in Scotland and this has taken various practical forms, which will come to be recorded in due course. This particular meeting must of necessity be viewed as something of an experiment, of which the success will guide the Council in its future efforts of a similar nature. It is the intention to ask for the cooperation of local astronomical societies in arranging any such meeting and, of course, to invite the attendance of their members and those of other local scientific bodies.

The Council's action in regard to *Occasional Notes* arises from a determination to give more systematic effect to its original intentions in starting this publication as expressed in the Foreword to the first issue. The Council proposes that *Occasional Notes* shall from 1948 appear at least three times per year and it is about to appoint an Editor and a small editorial board to have special charge of its production. After careful deliberation the Council adheres to the view that *Occasional Notes* can provide a very acceptable service to Fellows different from that provided either by its own other publications or by *The Observatory*, which it continues to distribute to Fellows. In order to ensure, however, that it shall not encroach upon the proper domain of *The Observatory*, it has arranged for the Editors of that journal to be represented on the editorial board of *Occasional Notes*.

To return to the narrative of the Council's activities, the year has again been extremely busy on the administrative side. Miss Wadsworth relinquished the post of Assistant Secretary on 1947 August 17. She had given unstinted service to the Society during five years of unprecedented difficulty and, as the Council recognized, for the most part without adequate assistance. The Council has placed on record its appreciation of her devotion to the interests of the Society. Miss Garratt, who had joined the Office staff as assistant to Miss Wadsworth towards the end of 1946, was appointed to succeed her from 1947 August 18. The Council is glad to announce that Miss Wadsworth has accepted appointment as Librarian (part-time), to commence duties on 1948 January 1. It has created this post, by at any rate temporarily separating the duties of Librarian from those of Assistant Secretary, in order to overtake war-time arrears in the library work and, more particularly, to facilitate the long overdue reorganization of the library.

One other action of the Council must receive some explanation here. When the balloting list for the new Council was in the hands of Fellows they will have seen that two of the nominees were described as "Editor of *Monthly Notices*" and "Editor of *Geophysical Supplement*", respectively. The latter is the member appointed by the Council as Secretary of its Geophysical Committee and it has been the practice, ever since the inception of the *Geophysical Supplement*, that the member so appointed should edit that publication. The proposal to have a separate Editor of *Monthly Notices* is, on the other hand, a new one for recent times, though there is good precedent for it in the earlier history of the Society, no less a person than Professor Arthur Cayley having held such an appointment from 1859 to 1881. Since 1881 the duty has been reckoned amongst those attached to the office of Secretary and has in fact been rightly regarded

as the foremost of those duties. However, under present conditions the Secretaries' other duties have become so heavy that the Council deems it essential to give them some relief. But the Secretaries will continue to deal with communications received until the Council reaches its final decision regarding their publication. The new proposal is to delegate to another member of the Council work subsequent to that stage, and not, of course, to delegate the responsibilities laid upon the Secretaries by the existing Bye-laws. The Society will doubtless feel grateful to those Fellows who are prepared thus to share the present burden of work of its Officers.

Some other special activities of the Council will be mentioned under particular headings below. For the rest, the Report follows the standardized form of recent years, with the addition that, for the first time since 1939 it is possible to include the List of Exchanges of publications.

2. *Loyal Address.*—The Society, through the Home Secretary, presented a Loyal Address to His Majesty the King, the Patron of the Society, on the occasion of the marriage of Her Royal Highness the Princess Elizabeth to His Royal Highness the Duke of Edinburgh. The text of the Address and that of the Home Secretary's reply conveying to the President the thanks of His Majesty are printed in *Monthly Notices*, Vol. **107**, pages 332 and 407.

3. *Eddington Gold Medal.*—As the President announced at the November Meeting of the Society, the Council has agreed to commemorate the services to astronomy of Sir Arthur Stanley Eddington by instituting an Eddington Gold Medal to be awarded, at such intervals as Council may deem appropriate and as funds available permit, for outstanding work in theoretical astronomy, more especially in those branches to which Eddington contributed most, but not excluding celestial mechanics. An appeal will be launched to establish this memorial.

4. *Isaac Newton Observatory.*—The Society was informed during May that the Admiralty and Treasury had agreed to the following composition of the Board of Management of the Isaac Newton Observatory.*

> The Astronomer Royal (Chairman), the Astronomer Royal for Scotland, the Director of the Cambridge Observatories and the Director of the Oxford University Observatory, to be four *ex-officio* members; four Fellows of the Royal Society appointed by the Council of the Royal Society, and four Fellows of the Royal Astronomical Society appointed by the Council of the Royal Astronomical Society, each of these to serve normally for four years, one of each four retiring in rotation each year; the Secretary of the Royal Observatory to be Secretary of the Board. This Board will report through the Astronomer Royal to the Board of Visitors of the Royal Observatory.

* Annual Report of the Council, *M.N.*, **107**, 4, 11, 15, 1947.

The Council has appointed as the Society's four representatives Professor P. M. S. Blackett, Dr J. A. Carroll, Professor A. O. Rankine and Professor F. J. M. Stratton. It was informed that the representatives of the Royal Society are Dr C. R. Burch, Lord Cherwell, Sir Thomas R. Merton and Sir Geoffrey I. Taylor.

When the Board's first report is presented it will show that the Board has lost no time in energetically embarking upon its task of bringing the 100-inch telescope into being.

5. *Bye-laws.*—The Annual General Meeting on February 14 gave its approval to the changes in the Bye-laws required by the Council's proposal to increase the Annual Contribution of Fellows. The reasons which had compelled the Council very reluctantly to ask for this increase were briefly stated in last year's Report. In moving its adoption, the Secretary called attention to the fact that the Revenue Account for 1946 showed a net deficit of £540. That year had not seen the full resumption of the Society's pre-war activities. The Secretary had to inform Fellows that, on a full year's working with a normal office staff and a normal flow of publications, but without an increase in the Annual Contribution, it was estimated that the deficiency would amount to about £1500. He also reminded Fellows that this was the first increase to be proposed since the foundation of the Society in 1821.

Obviously, the agreed increase will not cover the estimated deficiency without also a substantial increase in the number of Fellows. The Council does not wish to disguise the fact that the developments of the Society's activities noted in the first paragraph of this Report are to a considerable extent deliberately designed to achieve such an increase. No apology is needed for this motive. The Society cannot achieve the objects for which it exists without adequate numerical and financial strength. It is, moreover, in itself a thoroughly worthy object to seek to bring into the Society as many as possible of those persons who would be glad to benefit by its activities once having been made properly aware of them. The Council is convinced that the number of such persons is in fact considerably in excess of the number who do at present become Fellows.

The only one of the new developments requiring the sanction of fresh Bye-laws is the establishment of Junior Membership. Such Bye-laws were proposed by the Secretaries on behalf of the Council at a Special General Meeting on 1947 December 12 and received the approval of the meeting. They provide that a Junior Member shall be entitled to attend all Ordinary Meetings, to use the Library, and to receive either *Monthly Notices* or the *Geophysical Supplement*, on payment of an annual contribution of one guinea, and shall have the right to receive other publications of the Society at a reduced cost. He may retain these privileges for four years from the beginning of the year of his election or until the end of the year in which he reaches the age of twenty-five, whichever is the shorter period. If he is proposed for admission as a Fellow before ceasing to be a Junior Member, and is then elected in the ordinary way, he shall not be required to pay the usual admission fee. In order not to infringe the Charter it has been necessary to stipulate that a Junior Member shall not have the voting rights of a Fellow nor be eligible to hold office in the Society. (The Council has subsequently decided that, until further notice, the reduced cost of other publications referred to above shall be half the published price.)

6. *Membership.*—The Council records with regret the deaths of two Associates (Paul Guthnick and Svante Elis Strömgren) and twenty-two Fellows; their deaths occurred in 1947 except where an earlier year is indicated.

Alice G. Bryant (1942)
Edward Baunton Ford (1945)
Andrew Fraser (1946)
George James Gibbs
Godfrey Harold Hardy
Edwin Thomas Holdaway
William Henry de Bargue Hubert
James More Hunter
Jan Krassowski
James Simeon Lewis
*Jacob Gerhard Lohse (1940)
William MacIntyre
*Annie Scott Dill Maunder
John Anthony Miller (1946)
Bert Perrott
William Henry Pick
*David Bedell Pickering (1946)
Clement Frederick Press (1946)
*Lord Rayleigh
*Charles Tallent Spencer
Arthur Robert Wesley
*Algernon Charles Legge Wilkinson

*Life Fellow.

Obituary Notices of the Associates and some of the above Fellows are given on pages 35-53.

A table giving detailed statistics of the Membership of the Society on 1948 January 1 is given on page 15.

7. *Finance.*—The Annual Accounts have been presented in the same form as in the previous year.

A sum of £1500 has been received from the Executors of the late Professor H. C. Plummer, which has been invested in the purchase of £1471 4*s.* 0*d.* 3 per cent Savings Bonds 1955/65 to form a Trust Fund.

Consequent on the increase in composition fees, donations amounting to £87 11*s.* 0*d.* have been received from Fellows who compounded before the composition fees were raised, as a contribution towards the increased expenses of the Society. This amount has been added to the Composition Fees Fund.

The Revenue Account shows a deficit on the year, after the adjustment of reserves, of £971 6*s.* 1*d.* This deficit is caused mainly by increases in salaries and by the heavy increase in the cost of printing. The total printing costs for the year amount to £2455 10*s.* 8*d.* A grant of £500 was received through the Royal Society from the Parliamentary Grant-in-Aid for Scientific Publications. The increase in annual contributions from the beginning of 1948 will not in itself be sufficient to balance the Revenue Account, if expenses remain at their present high level, unless there is a substantial increase in the Fellowship.

The investments of the General Fund and the Trust Funds show an appreciation in value at the end of the year of £4767 over the valuation at 1922 December 29 or at subsequent cost. This appreciation is due to the decrease in interest rates and is not related to any increase in annual income.

8. *Meetings during* 1947.—The normal number of meetings were held in accordance with the revised Bye-laws of 1946. The President (Professor H. H. Plaskett) delivered his Address on "Astronomical Spectroscopy" at the Anniversary Meeting: this is printed in *Monthly Notices*, Vol. **107**, page 117; the George Darwin Lecture was delivered at the May meeting. The remaining

meetings were devoted mainly to the reading of original papers communicated to the Society. But opportunities were taken to invite various astronomers visting this country to speak about their current work; these included Professor G. A. Shajn (Simeis, U.S.S.R.), Dr R. H. Stoy (Cape Observatory), Dr R. Wildt (Yale), Professor H. Zanstra (Amsterdam). Several Fellows have also given much appreciated reports on astronomical topics of current interest, such as the exceptional solar activity of recent months. Finally, at the December meeting, Fellows saw with intense interest a motion film of prominences, "Explosions on the Sun", taken at Climax, Colorado, and presented to the Society by Professor D. H. Menzel, as well as the copies of two of Dr B. Lyot's films recently purchased by the Society.

The level of interest and enthusiasm shown at the meetings has been most marked and has been one of the most encouraging features of the year's activities. The average attendance of Fellows (as shown by signatures in the Attendance Book, and excluding visitors) was 70 as compared with 67 in 1946.

The pre-war practice of circulating announcement cards for each meeting has been resumed; they are sent to all Fellows who inform the Assistant Secretary of their wish to receive them.

9. *Geophysical Discussions.*—During the year, six discussions were held, covering a wide range of subjects. In conjunction with one on "Modern Methods of Timekeeping" a small exhibition of quartz crystal controlled frequency standards was arranged in the Grove Hills Library. The numbers attending these discussions have shown a marked increase above pre-war figures. While this clearly indicates their popularity, the limited accommodation may make it necessary on certain future occasions to restrict attendance to Fellows, Junior Members and their guests.

10. *George Darwin Lecture.*—Professor Marcel Gilles Jozef Minnaert, of Utrecht, Holland, gave the George Darwin Lecture at the Ordinary Meeting on May 9, taking as his subject "The Fraunhofer Lines of the Solar Spectrum". This address is printed in *Monthly Notices*, Vol. **107**, pages 274–290.

11. *Award.*—The Council awarded the Gold Medal of the Society to Professor Marcel Gilles Jozef Minnaert for his outstanding contributions to Solar Physics in general and Solar Spectrophotometry in particular.

12. *Publication and Printing.*—During the year 1947 the Society has published and distributed *Monthly Notices*, Vol. **106**, Nos. 2, 3, 4 and 5, *Geophysical Supplement*, Vol. **5**, No. 5, *Occasional Notes*, Nos. 10 and 11, and new editions of the *Bye-laws* and of the *List of Fellows*. There are in print, but not yet published, *Monthly Notices*, Vol. **106**, No. 6, Vol. **107**, Nos. 1, 2, 3, and *Geophysical Supplement*, Vol. **5**, No. 6.

After the unfortunate setback of 1946 in the Society's programme of printing, followed by that due to the fuel crisis early in 1947, this output is reasonably encouraging. It certainly reflects credit upon the work of Messrs Taylor & Francis, who took over the Society's printing at the end of 1946. Nevertheless the Council is seriously concerned at not having yet begun to overtake the delay in publication caused by the difficulties of the previous year. It feels it can,

however, look forward to an improved prospect for 1948, and that it is not too much to hope that, by the end of 1948, the present delay will have been about halved. If this hope is fulfilled, the Council will probably revert to the pre-war number of issues for Vol. **109**, but it has decided to restrict Vol. **108** to six issues.

It may not be out of place to remark that authors themselves can cooperate in achieving a return to speedier publication of their work both by ensuring that their "copy" is as clear as possible from the compositor's point of view, and so reducing the time required for setting it up in type and for subsequent corrections from the proofs, and also by returning proofs as expeditiously as possible.

13. *Exchange of Publications.*—Acting on information secured by the Astronomer Royal concerning present astronomical activities in the western zones of Germany, the Council has come to a provisional arrangement for transmitting the Society's publications to the main centres of these activities. Also a certain number of German astronomical journals have resumed publication during the year and the Council is trying to ensure their receipt by the Society.

The Council is gratified to include the publication of the Exchange List in this Report. A great deal of work has gone into its preparation. It is, of course, easy to say that the Council's object is to ensure that the Society's publications shall be reasonably accessible to all scientists, throughout the world, who require to consult them. While this certainly is the case, the Council cannot be as liberal as it could wish, owing to paper restrictions and financial considerations. It therefore hopes that, in the majority of cases in which an exchange has had to be declined, the institution concerned will find that the publications have been made available elsewhere in its neighbourhood or will be in a position to buy the publications for itself. The Council has also been bound to take into account the interest to Fellows of the publications offered in exchange. Finally, since the last revision of the List, many institutions have changed their designations or their locations or have transferred their work to other institutions, and it has been no light task to collect the necessary information. For such reasons the present List may suffer from a number of imperfections which the Council will be anxious to correct in the light of further knowledge.

14. *Library.*—The use made of the Library shows a marked increase; in 1947 the number of books borrowed was 608 by 134 different borrowers as compared with 420 books and 117 different borrowers in 1946. Visits to the Library for consultation show a decrease from last year, being about 95 a month.

During the year two lists of *Additions to the Library*, other than by exchange, covering additions up to 1947 July 31 were circulated with *Monthly Notices*. A list of those who presented gifts to the Library, other than by exchange, is given on page 33. The Society took advantage of the opportunity given it by Mr G.H. Wyatt of buying his copy of Newton's *Philosophiae Naturalis Principia Mathematica*, Second Edition, with which a copy of the first edition of *Commercium Epistolicum* is bound. The Society is indebted to Professor Heckmann and Professor Kienle for obtaining copies of German publications for the Society but in spite of such help there are still gaps in some series.

A consignment of serials was sent to the binders early in 1946 but this had

not been returned by the end of the year. Next year it is intended to employ more than one firm of binders in an endeavour to make up the arrears.

The re-arrangement and re-cataloguing of the Library, on which it was hoped to make a start during the year, has not been begun.

15. *Slides, prints and instruments.*—It is gratifying to report that the Society's stock of slides and prints available for purchase by Fellows is now being gradually replenished. Also, with the friendly cooperation of the observatories concerned, a number of new items have been added to the Society's collection.

The Council has decided to make a collection of the slides available for loan to Fellows on payment of a small fee in addition to the cost of packing and postage.

Reproductions of all three films mentioned in paragraph 8 may be hired by Fellows for their personal use.

A few fresh loans of instruments belonging to the Society have been made and the majority of existing loans have been renewed.

The care of the Society's Harrison Clock has since 1927 been the responsibility of Commander R. T. Gould (see *Monthly Notices*, **89**, 398, 1929; **106**, 12, 1946). He has recently been compelled by ill-health to hand over this responsibility to Messrs C. Frodsham and Co., to whom he has given a full written account of its working, though he still inspects the clock whenever possible. The Council has recorded its appreciation of Commander Gould's many services in this connection.

16. *The Society's Staff.*—As already noted, Miss M. F. M. Garratt, B.Sc. succeeded Miss E. Wadsworth, M.A. as Assistant Secretary in August. Miss Wadsworth was appointed Librarian (part-time) but was granted leave of absence until the end of the year. Miss J. Bower, who had been shorthand-typist in the Office for two years, left in September and was succeeded by Miss U. M. Samuelson. Mrs U. M. Dewey and Miss H. M. Fairweather have given valuable temporary assistance during periods of illness and leave of other members of the staff.

17. *The Society's Premises.*—The boiler of the heating system cracked in November and has hitherto resisted attempts to repair it. For use during the long interval which is expected to elapse before a new boiler can be installed under present circumstances, the Ministry of Works has supplied a number of oil stoves, which should make it possible to continue to hold meetings in the Society's rooms for the remainder of the winter. The stoves were not, however, in use in time for the December meeting. The Society is deeply grateful for the hospitality of the Linnean Society of London on that occasion.

Fellows will have noted with satisfaction that the series of Presidents' portraits in the Meeting Room is now complete and up to date, it having become possible to obtain frames and glass for recent additions.

18. "*The Observatory*".—In accordance with the agreement recorded last year, the six issues of *The Observatory* for 1947 have been distributed to Fellows.

19. *Guest Societies.*—The British Astronomical Association and the London Mathematical Society have held their normal number of meetings in the Society's

rooms. Meeting accommodation has been granted to the Corporation and the Council of the Norman Lockyer Observatory and to the British Association Tables Committee and, on one occasion, to certain Sectional Committees of the British Association.

20. *Representation of the Society.*—Professor Otto Struve represented the Society at the installation of the new President of the Rice Institute on April 10. The Society was represented at the Centenary Celebration of the Chemical Society in July and presented a congratulatory Address on the occasion. The Society was represented also at the Memorial Service for Lord Rayleigh on December 17.

In addition to the customary regular representation of the Society on a number of outside bodies, the Council has appointed representatives on various special Committees: the Royal Society Committee on the Accommodation of Scientific Societies, the Physical Society Committee on the participation by Great Britain in the work of the International Commission on Optics, and the Steering Committee of the Institute of Navigation. Professor Stratton represented the Society at the Inaugural Meeting of the Institute of Navigation and conveyed the Society's good wishes.

21. *Acknowledgments.*—The Council cordially acknowledges its indebtedness to the President and Council of the Linnean Society of London for the use of their Meeting Room and Council Room on December 12, and to the Director of the Science Museum for providing a film-projector and operator on the same occasion.

REPORT OF THE AUDITORS FOR THE YEAR 1947

We have examined the Treasurer's accounts of receipt and expenditure and approve the various items therein. This year once again there is an excess of expenditure over revenue, and this is indeed greater than in the previous year. The increase of the subscription from two to three guineas a year will, no doubt, go a long way towards restoring balance. In this connection we are happy to report that this increase in the amount of the subscription has not so far resulted in a decrease in the number of Annual Subscribers through resignations.

We have checked the official list of Fellows against subscriptions received, and we are glad to report an increase in the total number of Fellows. This is only in part due to the payment of arrears by previously non-active Fellows.

A list has been prepared containing the names of Fellows who are in arrear for sums due on 1947 January 1. Just over half of the names on the list include Fellows whose contributions are unobtainable under War Conditions. We think that it may well be impossible to re-establish contact with some of these Fellows and we accordingly beg to suggest that the Suspense Account be discontinued at some date in the near future. A list of their names should, however, be kept for reference but not included in the next list of Fellows when this is prepared.

We again recommend that the artificial lighting of the Society's rooms be improved.

Finally, it is a pleasure to express our thanks to the Assistant Secretary for her help and for the information she kindly placed at our disposal.

V. C. A. FERRARO.

F. M. PEACHEY.

PROGRESS AND PRESENT STATE OF THE SOCIETY

	Patron	Institutional Members	Fellows			Associates	Total
			Compounders	Annual Contributors	Non-active Fellows		
1947 January 1	1	5	199	633	51	49	938
Since elected...	...	...	+ 1	+66	...	...	...
Fellowship resumed...	...	...	+ 1	+ 2	...	...	...
Deceased 1947	...	...	− 3	− 9	...	− 2	...
Deceased prior to 1947, death not notified	...	...	− 2	− 2	...	...	...
Resigned 1947	...	...	...	−19	...	...	...
Since compounded	...	...	+13	−13	...	...	...
Suspense Account :—							
Deducted 1947 :							
Deceased prior to 1947, death not notified—" War conditions " Bye-law 26A	...	...	...	...	− 3	...	...
Transferred 1947 :							
(*a*) From "War conditions" 1946 to Active...	...	..	+ 1	+ 4	− 5	...	...
(*b*) From Bye-law 26A 1946 to Active...	...	...	...	+ 4	− 4	...	...
(*c*) From Bye-law 26B 1946 to Active...	...	...	...	+ 1	− 1	...	...
1948 January 1	1	5	210	667	38	47	968

(N.B.—Eight Associates are also Fellows, and are therefore counted twice in the above table.)

Cash

RECEIVED	£ s. d.	£ s. d.	£ s. d.
Balances, 1947 January 1 :—			
In hand of Assistant Secretary, on Petty Cash Account		7 3 9	
At Westminster Bank, on Current Account		904 2 1	
At Westminster Bank, on " B " Account :—			
A. S. Williams Bequest		52 10 0	
At Westminster Bank, on " C " Account :—			
Trust Funds	£423 11 10		
Sales of Duplicate Books Fund	17 10 7		
		441 2 5	
At Post Office Savings Bank :—			
General Fund	£3,282 19 2		
" C " Account	688 4 4		
Staff Pension Fund	464 12 1		
		4,435 15 7	
At London Savings Bank :—			
Ordinary Department (including £250 A. S. Williams Bequest)	£1,156 0 0		
Special Investment Department	584 12 9		
		1,740 12 9	
			7,581 6 7
Legacy from Plummer Bequest			1,500 0 0
Parliamentary Grant-in-Aid for Scientific Publications, received through the Royal Society for 1947			500 0 0
Dividends on Investments		648 18 6	
Interest on Savings Banks Deposits		146 11 0	
Income Tax refunded : 1946 April–December	£131 13 2		
1947 January–April	83 14 0		
		215 7 2	
Sales of Publications :—			
For 1947	£541 5 11		
Due in 1946	16 12 5		
1948 in advance	28 3 0		
		586 1 4	
Reprints :—			
For 1947		8 8 0	
Sale of Photographs and hire of slides, 1947		22 16 11	
Miscellaneous Receipts :—			
London Mathematical Society	£30 0 0		
Assistant Secretaries, Contributions to Pension Schemes	24 16 4		
Excess on Contributions	13 5		
Postages repaid : 1946	8		
1947	30 16 3		
Postages 1948, paid in advance	2 2 0		
British Astronomical Association, 1947	120 0 0		
Special Contribution, J. C. Boyce	1 18 0		
Hire of Films	10 0		
		210 16 8	
			1,838 19 7
Received on Account of Contributions :—			
560 Annual Contributions, 1947, *less* 18s. paid in 1946	£1,170 18 0		
4 Institutional Membership Fees	8 8 0		
18 Annual Contributions, 1948, in advance, and 17 partial Contributions	89 8 6		
1 Annual Contribution, partial, 1949, in advance	1 17 0		
59 Admission Fees, 1947	123 18 0		
59 First Contributions, 1947	109 4 0		
		1,503 13 6	
Arrears paid off :—			
1 1929	£2 2 0		
1 1930	2 2 0		
1 1931	2 2 0		
1 1939	2 2 0		
2 1940	4 4 0		
3 1941	6 6 0		
4 1942	8 8 0		
4 1943	8 8 0		
3 1944	6 6 0		
7 1945	14 14 0		
21 1946	44 2 0		
1 Institutional Membership Fee, 1946	2 2 0		
1 Admission Fee and First Contribution, 1946	3 3 0		
		106 1 0	
Compositions :—			
15 Reduced	£276 13 6		
Special Appeal Receipts	87 11 0		
		364 4 6	
			1,973 19 0
" C " Account :—			
Dividends on Investments		171 16 10	
Income Tax refunded		19 10 8	
Interest on Post Office Savings Bank Account		17 4 0	
Sales of Duplicate Books and Instruments		7 0 0	
			215 11 6
			£13,609 16 8

Account

PAID

	£ s. d.	£ s. d.	£ s. d.
Office Staff : Salaries	£904 14 2		
Income Tax on Salaries	154 16 0		
Health and Unemployment Insurance	10 18 2		
Assistant Secretaries : Pension Premiums (Society's Contributions £45 ; Assistant Secretaries' Contributions £46 13s. 2d.)	91 13 2		
		1,162 1 6	
Porter and Wife : Wages and Cleaning	£238 15 6		
Health and Unemployment Insurance	11 4 10		
Pension Contribution	13 0 0		
		263 0 4	
Charwoman : Wages		28 12 0	
			1,453 13 10
Insurance		31 11 6	
Telephone		27 1 8	
			58 13 2
Printing, etc. :—			
Monthly Notices (Vol. **106**, Nos. 2, 3, 4)		681 16 10	
Occasional Notes, No. 10		95 0 0	
Geophysical Supplement, Vol **5**, No. 5		123 19 6	
Reprints		17 4 5	
Charter and Bye-laws		51 19 10	
Miscellaneous		85 16 1	
Photo-engraving		198 15 5	
Paper for Publications		214 2 7	
			1,468 14 8
Postages and Packing :—			
Monthly Notices, etc.		58 13 11	
Office Postages		83 6 8	
			142 0 7
Stationery and Office Expenses		198 15 8	
Heating and Lighting		172 4 9	
Accountants' Fee		31 10 0	
Subscription to Committee on Library Cooperation		1 1 0	
Subscription to A.S.L.I.B.		3 3 0	
I.A.U. Telegrams		5 5 0	
Authorized Travelling Expenses		14 6 0	
Repairs, Fittings and Fixtures		247 5 5	
House Expenses and Laundry		41 12 3	
Expenses of R.A.S. Meetings and Committees		53 4 8	
Porter's Uniform		4 4 0	
Bank Charges and Cheque Books		2 5 4	
Library Expenses		5 13 9	
Gold Medal		10 12 6	
Miscellaneous Expenditure		27 19 1	
			819 2 5
Reproduction of Slides and Prints			116 6 9
Purchase of Books From Potter Fund			33 18 11
Binding Periodicals			44 3 0
Headley Observatory :—			
Rent of Observatory Paddock	£5 0 0		
Insurance of Buildings and Instruments on Site	1 6 6		
Mr Maskell for care of Site	7 10 0		
Repairs to Buildings	2 0 0		
		15 16 6	
Less Contribution from British Astronomical Association	£5 0 0		
Contribution from Dr R. L. Waterfield	3 1 1	8 1 1	
			7 15 5
Block Subscription to *The Observatory*			135 0 0
Investment of Legacy from Plummer Bequest :—			
£1,471 4s. 0d. Savings Bonds 3% 1955/65			1,500 0 0
Expenditure on Trust Accounts :—			
Turner and Horrocks Fund (Library)		4 15 0	
Harry Watson Fund (Library)		8 10 10	
George Darwin Lectureship Fund		50 0 0	
Sales of Duplicate Books Fund		10 10 0	
			73 15 10
Balances, 1947 December 31 :—			
In hand of Assistant Secretary, on Petty Cash Account		16 4 8	
At Westminster Bank, on Current Account as per Pass Book	395 10 4		
Less Cheques not yet presented	113 10 4		
		282 0 0	
At Westminster Bank, on " B " Account (A. S. Williams Bequest)		52 10 0	
At Westminster Bank, on " C " Account :—			
Trust Funds, as per Pass Book	£553 18 6		
Less Cheques not presented	2 5 0		
	£551 13 6		
Sales of Duplicate Books Fund	14 0 7		
		565 14 1	
At Post Office Savings Bank :—			
General Fund	£3,874 8 2		
" C " Account	705 8 4		
Staff Pension Fund at 1946 December 31	£464 12 1		
Add Interest, 1947	11 12 0		
	476 4 1		
		5,056 0 7	
At London Savings Bank :—			
Ordinary Department (including £250 A. S. Williams Bequest)	£1,184 18 0		
Special Investment Department	599 4 9		
		1,784 3 9	
			7,756 12 1
			£13,609 16 8

Dr. *General Fund Revenue Account*

	£	s.	d.	£	s.	d.
To Salaries and Wages, including Pension Premiums and National Insurance				1,417	16	8
,, Insurance and Telephone (after adjusting Reserves)				60	5	1
,, Printing, etc. (after adjusting Reserves)	2,455	10	8			
Less Amount received from the Parliamentary Grant-in-Aid for Scientific Publications through the Royal Society for 1947	500	0	0			
				1,955	10	8
,, Posting and Packing (after adjusting Reserves)				189	7	1
,, *General Expenses* (*after adjusting Reserves*) :—						
Stationery and Office Expenses	198	15	8			
Lighting and Heating	162	12	2			
Travelling Expenses	14	13	6			
Subscriptions to Committee on Library Cooperation and A.S.L.I.B.	4	4	0			
Accountants' Fee, 1946 (additional) £10 10 0						
1947 ... ... 31 10 0						
1947 Special Assistance ... 15 15 0						
	57	15	0			
Gold Medal	10	12	6			
Office Furniture and Fittings, including repairs	103	18	0			
I.A.U. Telegram Service	5	5	0			
Sundries	124	12	8			
				682	8	6
,, Block Subscription to *The Observatory*				135	0	0
,, Purchase of Books from Potter Fund				33	18	11
,, Headley Observatory, Expenses *less* Refunds				8	6	6
,, Annual Reserve for Repairs				40	0	0
				£4,522	13	5

One Year to 1947 *December* 31 *Cr.*

	£ s. d.	£ s. d.	£ s. d.
By *Amounts received from Fellows* :—			
1 Arrear for 1929	2 2 0		
1 „ „ 1930	2 2 0		
1 „ „ 1931	2 2 0		
1 „ „ 1939	2 2 0		
2 Arrears for 1940	4 4 0		
3 „ „ 1941	6 6 0		
4 „ „ 1942	8 8 0		
4 „ „ 1943	8 8 0		
3 „ „ 1944	6 6 0		
7 „ „ 1945	14 14 0		
22 „ „ 1946 (including 1 Institutional Membership Fee) ...	46 4 0		
1 Arrear, Admission Fee and First Contribution, 1946	3 3 0		
596 Annual Contributions for 1947 (including Prepayments in 1946)	1,251 12 0		
4 Institutional Membership Fees	8 8 0		
59 Admission Fees	123 18 0		
59 First Contributions	109 4 0		
		1,599 3 0	
Composition Fees :—			
Reduced Fees	276 13 6		
Special Appeal	87 11 0		
	364 4 6		
Less Transferred to Reserve Account ...	364 4 6		
	— — —		
Add Amount brought to Credit for the year	112 10 7		
		112 10 7	
			1,711 13 7
„ Interest and Dividends received (gross)		864 5 8	
„ Interest on Bank Deposit Accounts received		134 19 0	
			999 4 8
„ Sales of Publications, Photographs and Miscellaneous Receipts for the year			840 9 1
„ Deficiency one year to date			971 6 1
			£4,522 13 5

Note.—Fellows' 1947 Contributions not received were :—

23 Unobtainable under War conditions	48 6 0	
9 Waived under Bye-law 26A	18 18 0	
6 Waived under Bye-law 26B	12 12 0	
30 Others unpaid at 1947 December 31	63 0 0	
1 Institutional Membership Fee, ditto	2 2 0	
Total for the year	£144 18 0	

This amount has been added to the Suspense Account and is not included in this Revenue Account.

Balance Sheet

	£ s. d.	£ s. d.	£ s. d.
General Fund :—			
As at 1946 December 31	22,503 7 6		
Less Excess of Expenditure over Income, 1947	971 6 1		
			21,532 1 5
Trust Funds :—			
Capital as at 1946 December 31	£5,207 0 3		
Add Plummer Bequest	1,500 0 0		
	6,707 0 3		
Income Balances at 1947 December 31	1,257 1 10		
Income Tax on Trust Funds, 1947 April–December, not yet refunded	19 10 8		
			7,983 12 9
Reserves :—			
Repairs and Maintenance :			
As at 1946 December 31	£240 0 0		
Add Set aside for 1947	40 0 0		
	280 0 0		
Replacements of Photographic Slides and Prints :			
As at 1946 December 31	213 16 2		
Less Expenditure for the year 1947	111 17 3		
	101 18 11		
Binding War-time Periodicals :			
As at 1946 December 31	150 0 0		
Less Expenditure 1947	44 3 0		
	105 17 0		
Sales of Duplicate Books Fund :			
As at 1946 December 31	17 10 7		
Add Received from Duplicate Books and Instruments sold	7 0 0		
	24 10 7		
Less Books purchased	10 10 0		
	14 0 7		
			501 16 6
Composition Fees Reserve Fund :—			
As at 1946 December 31	1,511 5 5		
Received in 1947	276 13 6		
Special Appeal in 1947	87 11 0		
	1,875 9 11		
Less 6 per cent transferred to Revenue Account	112 10 7		
			1,762 19 4
Staff Pension Fund :—			
As at 1946 December 31	464 12 1		
Add Interest for the year	11 12 0		
			476 4 1
Amounts received in advance :—			
Contributions :			
1948 paid in 1945	£2 2 0		
1949 paid in 1945	1 12 0		
1948 paid in 1946	4 16 6		
1949 paid in 1946	2 12 0		
1948 paid in 1947	89 8 6		
1949 paid in 1947	1 17 0		
	102 8 0		
Publications, 1948	28 3 0		
Postages, 1948	2 2 0		
			132 13 0
Sundry Creditors for Accounts due but not presented (including provision for printing publications for the years 1946 and 1947, not yet completed) ...			2,733 18 8
			£35,123 5 9

To the Fellows of THE ROYAL ASTRONOMICAL SOCIETY.

We have examined the above Balance Sheet with the Books and Vouchers relating thereto explanations given to us.

We have verified the Securities representing the Investments and have found them to be

1947 *December* 31

	£	s.	d.	£	s.	d.
Investments :—						
General Fund, valued as at 1922 December 29 or subsequent cost...	20,374	11	1			
Trust Funds, valued at cost	6,707	0	3			
(Market Value 1947 December 31, £31,849)				27,081	11	4
Debtors :—						
General	133	18	6			
Income Tax Recoverable :						
General Fund	131	13	2			
Trust Funds	19	10	8			
				285	2	4
Deposits at Savings Banks :—						
General Fund	£6,134	15	0			
Trust Funds	705	8	4			
	6,840	3	4			
Cash on Current Account at Bank and In Hand :—						
General Fund	350	14	8			
Trust Funds	565	14	1			
	916	8	9			
As per Cash Account				7,756	12	1
				£35,123	5	9

Note.—Fellows' Contributions unpaid at 1947 *December* 31 : £669 18*s.* 0*d.* *This amount represents the total of the Suspense Account and is not included in this Balance Sheet.*

and certify it to be correctly drawn up therefrom and in accordance with the information and in order.

SUFFOLK HOUSE,
5 LAURENCE POUNTNEY HILL, LONDON, E.C. 4,
1948 February 9.

SHARP, PARSONS & CO.,
Chartered Accountants.

INVESTMENTS

As at 1947 December 31

General Fund

£2000 Swansea Corporation 3½ per cent Stock.
£5125 London, Midland and Scottish Railway 4 per cent Debenture Stock.*
£750 London, Midland and Scottish Railway 4 per cent Preference Stock.*
£2400 Gas Light and Coke Co. 3 per cent Consolidated Debenture Stock.*
£2000 Commercial Gas Co. 3 per cent Debenture Stock.*
£496 Consolidated 4 per cent Stock, 1957.
£1035 Agricultural Mortgage Corporation, Ltd., 4½ per cent Debenture Stock, 1961–91.*
£1000 Hull Corporation 4½ per cent Redeemable Stock, 1952–72.
£1000 Central Electricity Board 4½ per cent Stock, 1957–82.*
£700 Birmingham Corporation 3 per cent Inscribed Stock, 1947.
£2280 5*s*. 3*d*. War Loan 3½ per cent Inscribed Stock.
£500 New South Wales 4 per cent Stock, 1942–62.*
£1156 1*s*. 5*d*. Metropolitan Water Board 3 per cent " B " Stock.
£500 National Defence Loan, 1954–58, 3 per cent Bonds.
£500 Savings Bonds 2½ per cent, 1964/67.
£2118 3*s*. 5*d*. Savings Bonds 3 per cent, 1960/1970. (Holding " A ")
£695 16*s*. 0*d*. Conversion Loan 3½ per cent, 1961.

Trust Funds

£1004 Consolidated 4 per cent Stock, 1957.
£965 Agricultural Mortgage Corporation, Ltd., 4½ per cent Debenture Stock, 1961–91.*
£491 10*s*. 0*d*. War Loan 3½ per cent Inscribed Stock.
£1160 16*s*. 3*d*. War Loan 3½ per cent Inscribed Stock.
£542 18*s*. 2*d*. Savings Bonds 3 per cent, 1960/1970. (Holding " B ")
£1122 19*s*. 6*d*. Savings Bonds 3 per cent, 1960/1970. (Holding " C ")
£1471 4*s*. 0*d*. Savings Bonds 3 per cent, 1955/1965.

* *Taxed at source.*

GIFTS TO THE GENERAL FUNDS AND PROPERTY OF THE SOCIETY

The John Lee Gift (1836 and 1844): In 1836 John Lee, Esq., LL.D., gave the Advowson of the living of Hartwell; in 1844 he gave the Advowson of the living of Stone, Bucks. In 1879 these Advowsons were purchased by his heir, Edward Lee, Esq., for £700.

The Lawson Bequest (1856): Henry Lawson, Esq., bequeathed to the Society the sum of £200, free of legacy duty.

The Carrington Bequest (1876): R. C. Carrington, Esq., F.R.S., bequeathed to the Society £2000 Consols.

The Lambert Bequest (1877): C. J. Lambert, Esq., presented to the Society the sum of £500 free of legacy duty, being part of a sum of money bequeathed by his father, Charles Lambert, Esq., for scientific purposes.

The McClean Bequest (1905): Frank McClean, Esq., LL.D., F.R.S., bequeathed to the Society the sum of £2000, free of legacy duty.

The Farrar Bequest (1906): The Rev. A. S. Farrar, D.D., bequeathed to the Society the sum of £100, free of legacy duty.

The Parsons Gift (1922): The Hon. Sir Charles Parsons, K.C.B., F.R.S., gave to the Society £2500 War Stock 1929–47, in memory of his father, the 3rd Earl of Rosse, who made the 6-foot reflector, and who died 1867 October 31.

The Grove-Hills Bequest (1922): Colonel E. H. Grove-Hills, C.M.G., F.R.S., bequeathed to the Society, free of legacy duty, his collection of early astronomical and mathematical books up to the year 1700, together with a sum of £250 to cover the expenses incurred by the Society in connection with the books.

The Grove-Hills Fund (1922): In 1922 the Treasurer, Colonel Grove-Hills, collected by his private efforts, with the approval of the Council, a Special Fund to meet the immediate financial difficulties of the Society. The total amount received from all sources (including dividends on the investments representing the fund) has been £1913 1*s.* 11*d.*, of which £1480 2*s.* 10*d.* has been invested and is now represented by £535 Agricultural Mortgage 4½ per cent, £423 15*s.* 11*d.* War Stock 3½ per cent, and £695 16*s.* Conversion Loan 3½ per cent 1961.

The Lindemann Bequest (1931): A. F. Lindemann, Esq., bequeathed to the Society the sum of £1000, free of legacy duty.

The Archdeacon Potter Bequest (1933) (*see page* 24).

The Goodridge Bequest (1936): Captain J. J. L. Goodridge, who died 1936 March 13, bequeathed to the Society the sum of £50, free of legacy duty. In 1937 the bequest was invested in £49 0*s.* 4*d.* War Stock 3½ per cent.

The Herbert Spencer Bequest (1936): Herbert Spencer, Esq., who died in 1903, nominated the Royal Astronomical Society as one of twelve Learned Societies to be eventual beneficiaries of his residuary estate. His estate was wound up in 1936, and the Society's share of the residue amounted to £1241. The conditions of acceptance of the legacy were that the sum received should be spent in certain specified ways by the Governing Body within five years of the date of payment, and might not be used in any way for purposes of endowment. The bequest was finally expended during 1941.

The Lindley Bequest (1937): Miss Julia Lindley bequeathed to the Society the sum of £1000, free of legacy duty, which was received from the Public Trustee in the form of £1156 1*s*. 5*d*. Metropolitan Water Board 3 per cent "B" Stock.

The Stanley Williams Bequest (1939): A. Stanley Williams, Esq., who died 1938 November 21, bequeathed to the Society all his astronomical instruments, books, maps, photographs, manuscripts, etc., together with the sum of £200, free of legacy duty, for the reduction or publication of his observations of variable stars; and also a further sum of £100, free of legacy duty, for the furtherance of astronomy in general or of the Society in particular, in such manner as the Council of the Society may think fit. No expenditure from the fund has been made up to 1947 December 31.

The Plummer Bequest (1946): H. C. Plummer, Esq., M.A., F.R.S., bequeathed to the Society the sum of £1000, to be invested and treated as a Trust Fund, the income to be at the disposal of the Council for all purposes, with a recommendation that they should consider the possibility from time to time of helping the Norman Lockyer Observatory. The Society was also named as one of the residuary legatees. In 1947 October, a first distribution, under the terms of the will, of £1500 was received from the Administrators of the Estate, which has been invested in £1471 4*s*. 0*d*. 3 per cent Savings Bonds, 1955/1965; this sum and any subsequent sum or sums which may be received from the Administrators will be used in accordance with the late Professor Plummer's wishes. No dividends were received by the Society in 1947.

SPECIAL FUND

The Archdeacon Potter Fund (1933): Archdeacon Beresford Potter, who died 1931 May 10, bequeathed to the Society a 3/88th share of his residuary estate. This legacy was received in 1933, and now stands invested in £300 3½ per cent War Stock, the cash balance of £17 15*s*. 2*d*. being expended on the library in 1934. The Council resolved to allocate the dividends from this fund for the purposes of the library.

	£	*s*.	*d*.		£	*s*.	*d*.
1947 Jan. 1. Balance of Fund...	42	6	10	1947. Purchase of Books ...	33	18	11
1947. Dividends, War Stock 3½ per cent	10	10	0	1947 Dec. 31. Balance of Fund...	18	17	11
	£52	16	10		£52	16	10

TRUST FUNDS

The Lee and Janson Fund (1834 and 1879): In 1834 John Lee, Esq., LL.D., gave £100, and in 1879 T. C. Janson, Esq., bequeathed £200, the interest to be given to the widow or orphan of a deceased Fellow. These amounts now stand in £309 16*s.* 3 per cent Savings Bonds, 1960/1970.

	£	*s.*	*d.*		£	*s.*	*d.*
1947 Jan. 1. Balance of Fund ...	70	4	8	1947 Dec. 31. Balance of Fund :—			
1947. Dividends, 3 per cent Savings Bonds	9	6	0	In P.O. Savings Bank £38 8 2			
Interest on P.O. Savings Bank Deposit	0	19	0	At Bank 42 1 6			
					80	9	8
	£80	9	8		£80	9	8

The Turnor Fund and the Horrocks Memorial Fund (1853 and 1876): In 1853 the Rev. Charles Turnor, M.A., bequeathed a sum of £500, which now stands in £430 10*s.* 4*d.* 3 per cent Savings Bonds, 1960/1970. In 1876 the Society received a sum of £38 15*s.*, the unexpended balance of a fund collected for the purpose of erecting a memorial in Westminster Abbey to Jeremiah Horrocks: to this the Society added the sum of £55 15*s.*, and the whole now stands in £95 13*s.* 2*d.* 3 per cent Savings Bonds, 1960/1970. The interest on these funds is to be used in the purchase of books for the library.

	£	*s.*	*d.*		£	*s.*	*d.*
1947 Jan. 1. Balance of Fund ...		15	6	1947. Purchase of Books ...	4	15	0
1947. Dividends, 3 per cent Savings Bonds	15	15	8	1947 Dec. 31. Balance of Fund...	11	16	2
	£16	11	2		£16	11	2

The Hannah Jackson (née Gwilt) Fund (1861): In 1861 Mrs Hannah Jackson (*née* Gwilt) gave £300 Consols, which now stands in £287 3 per cent Savings Bonds, 1960/1970; the interest to be given in medals or other awards in accordance with the terms of the Trust.

	£	*s.*	*d.*		£.	*s.*	*d.*
1947 Jan. 1. Balance of Fund ...	13	4	3	1947 Dec. 31. Balance of Fund...	21	16	3
1947. Dividends, 3 per cent Savings Bonds	8	12	0				
	£21	16	3		£21	16	3

The Harry Watson Memorial Fund (1923): In 1920 Mrs Watson presented to the Society the sum of £300 as a memorial to her late husband, Lieut.-Col. Harry James Watson, F.R.A.S., the interest on this sum to be used for the purchase of books for the library, such books to be indicated by a special book-plate. This gift now stands invested in £542 18*s.* 2*d.* 3 per cent Savings Bonds, 1960/1970. In 1923 Mrs Watson bequeathed a further sum of £958 17*s.* to the Society, which now stands invested in £965 Agricultural Mortgage 4½ per cent Stock. The Council resolved that these two sums should together constitute a Trust Fund, to be designated *The Harry Watson Memorial Fund*, to be used for the purchase and binding of books.

	£	s.	d.		£	s.	d.
1947 Jan. 1. Balance of Fund ...	406	12	8	1947. Purchase of Books ...	8	10	10
1947. Dividends, Agricultural Mortgage 4½ per cent ...	23	17	10	1947 Dec. 31. Balance of Fund:—			
Dividends, 3 per cent Savings Bonds	16	5	8	In P.O. Savings Bank £245 12 4			
Income Tax, 1946 April–1947 April, refunded	19	10	8	At Bank 218 3 8			
Interest on P.O. Savings Bank Deposit	6	0	0		463	16	0
	£472	6	10		£472	6	10

The George Darwin Lectureship Fund (1926): In 1926 Sir James Jeans presented to the Society the sum of £1000 for the endowment of an annual lectureship, to be called *The George Darwin Lectureship*, the lecture to be on some subject of interest to astronomers, preference being given, in electing a lecturer, to one normally resident outside the British Isles.

This sum now stands in £1004 Consolidated 4 per cent Loan. The income is annually applied to the purposes of the Trust in accordance with the terms of the Deed of Gift.

	£	s.	d.		£	s.	d.
1947 Jan. 1. Balance of Fund ...	134	8	0	1947 May. Lecture Fee ...	50	0	0
1947. Dividends, Consolidated 4 per cent Loan	40	3	2	1947 Dec. 31. Balance of Fund:—			
Interest on P.O. Savings Bank Deposit	3	6	6	In P.O. Savings Bank £136 7 7			
				Less: Temporary advance from "C" account 8 9 11			
					127	17	8
	£177	17	8		£177	17	8

The A. G. Stillhamer Trust (1937): A. G. Stillhamer, Esq., of Bloomington, Illinois, left all his property outright to Miss Maude S. Capps, of Bloomington; but on account of certain personal memoranda and conversation between Mr Stillhamer and Miss Capps, the latter resolved to carry out what she believed to have been Mr Stillhamer's wishes by the payment to the Royal Astronomical Society of the sum of 2500 dollars in cash, the conditions of acceptance being that the principal is to remain intact in the endowment fund of the Society,

and the income therefrom to be used annually * to pay expenses of scientific research or to purchase definite scientific instruments for use in scientific instruction or research. The bequest has been invested in £491 10*s*. War Stock 3½ per cent.

	£	*s.*	*d.*		£	*s.*	*d.*
1947 Jan. 1. Balance of Fund ...	164	11	4	1947 Dec. 31. Balance of Fund:—			
1947. Dividends, War Stock 3½ per cent	17	4	0	In P.O. Savings Bank	£102 15 4		
Interest on P.O. Savings Bank Deposit	2	10	0	At Bank	81 10 0		
					184	5	4
	£184	5	4		£184	5	4

The E. W. Brown Trust (1939): E. W. Brown, Esq., M.A., Sc.D., F.R.S., who died in 1938, bequeathed to the Society the sum of five thousand dollars, and desired that the income from the bequest should be used for assistance in the calculation of accurate orbits of the bodies of the solar system, such income as should not be used for this purpose being used for the general purposes of the Society. The bequest was received in 1939 July, and was invested in £1160 16*s*. 3*d*. War Stock 3½ per cent.

	£	*s.*	*d.*		£	*s.*	*d.*
1947 Jan. 1. Balance of Fund ...	321	19	9	1947 Dec. 31. Balance of Fund:—			
1947. Dividends, War Stock 3½ per cent	40	12	6	In P.O. Savings Bank	£181 14 6		
Interest on P.O. Savings Bank Deposit	4	8	6	At Bank	185 6 3		
					367	0	9
	£367	0	9		£367	0	9

LIST OF EXCHANGES

The Society exchanges publications with the following Institutions, etc.:—

Austria:
Akademie der Wissenschaften, Wien
Universitätssternwarte, Wien
Sonnen Observatorium, Kanzelhohe

Belgium:
Académie des Sciences de Belgique
Société Belge d'Astronomie
Observatoire Royal, Uccle
Institut d'Astrophysique, Liége

Czechoslovakia:
Astronomical Institute of the Charles University
National Observatory of the Czech Republic, Prague
State Observatory, Skalnaté Pleso
Masaryk University, Brno
Czechoslovak Astronomical Society

* Miss Capps, subsequently to the initial conditions of the Trust, agreed to the income not being expended annually.

Denmark:	Royal Academy of Sciences, Copenhagen
	Copenhagen Observatory
	Geodetic Institute, Copenhagen
Eire:	Royal Dublin Society
	Royal Irish Academy, Dublin
	Dunsink Observatory
Esthonia:	Tartu Observatory
Finland:	Society of Sciences, Helsingfors
	Observatory, Helsingfors
	Isostatic Institute, Helsingfors
France:	Académie des Sciences, Paris
	Société Astronomique de France
	Observatoire d'Abbadia
	Observatoire National, Besançon
	Observatoire de Bordeaux
	Observatoire de Lyon
	Observatoire de Marseille
	Observatoire de Meudon
	Observatoire de Nice
	Observatoire de Paris
	Observatoire de Strasbourg
	Observatoire de Toulouse
	Bureau International de l'Heure
	Bureau International de Seismologie
	Ecole Polytechnique, Paris
	Institut d'Optique
	Institut d'Astrophysique, Paris
	Institut de Physique du Globe, Paris
	Observatoire de Haute Provence, St. Michel
	Institut Henri Poincaré, Paris
	Union Geodesique et Geophysique International, Paris
Germany:	Remeis-Sternwarte, Bamberg
	Universitätssternwarte, Berlin-Babelsberg
	Sternwarte, Sonneberg
	Universitätssternwarte, Bonn
	Fraunhofer Institut, Freiberg
	Universitätssternwarte, Göttingen
	Hamburger Sternwarte, Bergedorf
	Hauptstation für Erdbebenforschung, Hamburg
	Bad. Landessternwarte, Königstuhl-Heidelberg
	Universitätssternwarte, Jena
	Reichanstalt für Erdbebenforschung, Jena
	Institut für theoretische Physik, Kiel

Sternwarte, München
Astrophysikalisches Observatorium, Potsdam
Astronomisches Rechen-Institut, Heidelberg
Preuss. Geodätisches Institut, Potsdam
Redaktion, *Astronomischer Jahresbericht*
Redaktion, *Astronomische Nachrichten*

Greece: Athens Observatory

Holland: Royal Academy of Sciences, Amsterdam
Astronomical Institute, Amsterdam
Leiden Observatory
Utrecht Astronomical Observatory
Kapteyn Laboratory, Groningen

Hungary: Astronomical Institute, Budapest
Konkoly Observatory, Budapest
Haynald Observatorium, Kalocsa

Italy: R. Accademia Nazionale dei Lincei
R. Accademia delle Scienze, Torino
Società Astronomica Italiana, Milano
Società "Urania", Torino
R. Osservatorio Astrofisico, Arcetri
R. Osservatorio Astronomico di Brera, Milano
Osservatorio, Bologna
Instituto Geofisico Italiano, Milano
Osservatorio di Capodimonte, Napoli
Osservatorio Astronomico della R. Università, Padova
Osservatorio Astronomico, Palermo
R. Osservatorio Astronomico di Roma
Specola Vaticana, Roma
R. Specola di Collurania, Teramo
R. Osservatorio di Pino Torinese
Pontificia Accademia delle Science, Vatican

Norway: Institute of Theoretical Astrophysics, Blindern

Poland: Cracow Observatory
Poznan University Observatory
Swider Geophysical Observatory
Torun Observatory
Warsaw Observatory
Institut d'Astronomie Pratique de l'École Polytechnique, Warsaw
Wroclaw Observatory

Portugal:	Academia das Sciencias, Lisboa
	Observatorio Astronomico, Coimbra
	Observatorio Astronomico, Lisboa
	Observatorio Central Meteorologica do Infante D. Luiz, Lisboa
	Editors of *Portugaliae Physica*, Lisboa
Roumania:	Faculty of Science, Bucarest
Spain:	Observatorio de Cartuja, Granada
	Observatorio Astronomico, Madrid
	Observatorio di Marina, San Fernando
	Observatorio del Ebro, Tortosa
	Instituto Nacional de Geofisica, Madrid
	Instituto Geografica y Catastral, Madrid
Sweden:	Royal Academy of Sciences, Stockholm
	Swedish Astronomical Society, Stockholm
	Royal Society of Sciences, Uppsala
	Stockholm Observatory, Saltsjobaden
	Lund Observatory
	Uppsala Observatory
	Meteorological Institute, Uppsala
Switzerland:	Naturforschende Gesellschaft, Basel
	Société de Physique et d'Histoire Naturelle, Genève
	Naturforschende Gesellschaft, Zürich
	Observatoire, Genève
	Observatoire, Neuchâtel
	Eidgenössische Sternwarte, Zürich
Trieste:	Osservatorio Astronomico
	Instituto Geofisico
Turkey:	Observatory, Istanbul
United Kingdom:	Royal Society
	Royal Society of Edinburgh
	Royal Geographical Society
	Royal Institution of Great Britain
	Royal Meteorological Society
	British Astronomical Association
	Cambridge Philosophical Society
	Leeds Philosophical and Literary Society
	London Mathematical Society
	Manchester Astronomical Society
	Manchester Literary and Philosophical Society
	Physical Society
	Royal Observatory, Greenwich
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University College, London
Meteorological Office
H.M. Nautical Almanac Office
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Editor of *Science Abstracts*
Editors of *Science Progress*

U.S.S.R.: Institute of Astronomy and Physics, Alma Ata
Institute of Geodesy, Moscow
Physical Institute, Moscow
Astronomical Council of the Academy of Sciences of the U.S.S.R.
Astronomical Observatory, Abastumani
Astronomical Observatory, Stalinabad
Academy of Sciences, Moscow
Engelhardt Observatory, Kasan
University Observatory, Kasan
Kiev Observatory
Odessa Observatory
Pulkovo Observatory
Institute of Theoretical Astronomy, Leningrad
Burakan Observatory, Erevan
Scientific Research Institute of Metrology and Standardization, Leningrad
Sternberg State Astronomical Institute, Moscow
Astronomical Observatory, Tashkent

Yugoslavia: Académie Royale Serbe, Belgrade
Astronomical Observatory, Belgrade
Acad. Sud-Slave des Sciences, Zagreb

India and Pakistan: Indian Academy of Sciences, Bangalore
Bombay Observatory
Kodaikanal Observatory
Survey of India, Geodetic Branch
Nizamiah Observatory, Hyderabad
Colaba and Alibag Observatories, Bombay

Ceylon: Colombo Observatory

China:	Hong Kong Observatory
	Zo-Sé Observatory
	National Geological Survey of China
East Indies:	Bosscha-Sterrewacht, Lembang, Java
Japan *:	National Research Council of Japan
	Azabu Observatory
	Imperial University, Tokyo
	Earthquake Research Institute, Tokyo
Algiers:	Bouzareah Observatory
Egypt:	Helwan Observatory, Egypt
South Africa:	Royal Society of South Africa
	South African Association for the Advancement of Science
	Royal Observatory, Cape of Good Hope
	Radcliffe Observatory, Pretoria
	Union Observatory, Johannesburg
Canada:	Royal Astronomical Society of Canada
	Royal Canadian Institute, Toronto
	Royal Society of Canada
	Dominion Observatory, Ottawa
	Dominion Astrophysical Observatory, Victoria, B.C.
	David Dunlap Observatory, Toronto
	McGill University, Montreal
U.S.A.:	American Academy of Arts and Sciences, Boston
	Astronomical Society of the Pacific
	Franklin Institute, Philadelphia
	National Academy of Sciences
	Seismological Society of America
	Allegheny Observatory
	Cincinnati Observatory
	Dearborn Observatory
	Dudley Observatory, Albany
	Harvard College Observatory
	Leander McCormick Observatory
	Lick Observatory
	Lowell Observatory, Flagstaff
	McDonald Observatory, Texas
	University of Michigan Observatory
	Mount Wilson Observatory
	Perkins Observatory, Ohio
	Princeton University Observatory
	Sproul Observatory, Swarthmore

* Exchange temporarily suspended

	U.S. Nautical Almanac Office, Washington
	Washburn Observatory, Madison
	Yale University Observatory
	Yerkes Observatory
	Bureau of Standards, Washington
	Geological Survey, Washington
	Smithsonian Institution
	U.S. Coast and Geodetic Survey
	Editor of *The American Journal of Science*
	Editor of *The Astronomical Journal*
	Editors of *The Astrophysical Journal*
	Editor of *Terrestrial Magnetism*
	Editor of *Popular Astronomy*
	Editor of *Sky and Telescope*
Mexico:	Tacubaya Observatory
	Tonantzintla Observatory
Argentine:	Asociación Argentina "Amigos de la Astronomia"
	Cordoba Observatory
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Brazil:	Rio de Janeiro Observatory
Chile:	Santiago Observatory
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	Royal Society of Tasmania
	Canberra Observatory
	Perth Observatory
	Riverview College Observatory
	Sydney Observatory
New Zealand:	New Zealand Astronomical Society
	Dominion Observatory, Wellington
	Carter Observatory, Wellington

LIST OF PUBLIC INSTITUTIONS AND OF PERSONS WHO HAVE PRESENTED GIFTS (OTHER THAN BY EXCHANGE) TO THE LIBRARY DURING THE YEAR 1947.

Aarhus, Ole Romer Observatoriet
Astronomical Society of Mexico
Astronomical Society of South Africa
Astronomical Society of Tasmania
British Council
British Interplanetary Society
Chinese Physical Society
Copenhagen, Nordisk Astronomisk Selskab
Erevan, Astronomical Observatory
Ghent, Sterrenkundig Instituut der Universiteit
Griffith Observatory, Los Angeles
Imperial Chemical Industries
International Astronomical Union
Kirkwood Observatory of the Indiana University
Lima, Sociedad do Ingenieros del Peru
Lisbon, Sindicato Nacional dos Engenheiros Geografos
London, Institute of Physics
Lourenço Marques, Technical Statistical Department
Mizusawa, International Latitude Service
New York, Academy of Sciences
Princeton University
Rome, Reale Accademia d'Italia
Royal Society
Royal Society of Arts
San Miguel, Observatorio de fisica Cosmica
H.M. Stationery Office
Tokyo, National Research Council of Japan
United Nations Educational Scientific and Cultural Organization
Warsaw, Geological Survey of Poland
Washington, Carnegie Institution
Washington, National Bureau of Standards

Professor F. Becker
Miss E. F. Bellamy
Professor P. M. S. Blackett
Miss C. M. Botley
Mr D. Brinkmann
Dr C. E. P. Brooks
Mr B. C. Browne
Dr S. Chandrasekhar
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The Rev. Dr M. Davidson
Mr P. Doig
Mr A. E. Douglass
Mme Flammarion
Mr A. W. Folks
Mr G. F. S. Hills
Mr L. G. H. Horton-Smith
Mr G. Jarnefelt
Mr M. A. R. Khan
Dr C. Luplau-Janssen
Sir Francis McClean
Mr G. F. M. Mees
Professor D. H. Menzel
Dr G. Merton
Mr A. H. Miller
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Professor H. P. Robertson
Dr J. O. Schmidt
Dr H. Slouka
Dr H. T. Stetson
Miss E. Williamson
Mr G. H. Wyatt
Professor E. Zinner

OBITUARY NOTICES

PAUL GUTHNICK, formerly Director of the University Observatory at Berlin-Babelsberg and Professor of Astronomy at the University of Berlin, died on 1947 September 6.

Guthnick's name will go down in the history of astronomy as that of a pioneer in the application of the powerful photoelectric methods to the measurement of the brightness of celestial bodies. His inventiveness, care and unfailing patience in carrying out his experiments overcame all obstacles and assured final success.

His love for astronomy developed early in his boyhood. Born on 1879 January 12 in Hitdorf (Rhineland), he was the son of A. J. H. Guthnick, a wine-merchant, who took a keen interest in Paul's eager study and love of nature. Unfortunately the latter was only 16 when his father died. He continued, however, to attend the Gymnasium and later entered the University at Bonn (1897–1901). At that time it was intended that he should turn from his favoured study of astronomy to the safer career of teaching. In 1901 he took his Ph.D. degree under his revered teacher Professor Fr. Küstner and shortly afterwards his teaching degrees in Mathematics and Natural Sciences.

By then, however, he had made up his mind to become an astronomer. A friend of his youth, Dr H. Kreusler, who later made a name in optics, recollects some events of these student days in a delightful note in *Die Sterne*, **5**, 62, 1925. Kreusler's parents lived in the same house in Bonn into which Guthnick's parents moved: "... The great moment came. We met, each of us his beloved telescope under his arm. His was made of tin and had an ingenious slow-motion with strings. Mine was of cardboard only, but it had a clockwork drive and was equatorially mounted. . . It is of unique and indescribable beauty when two young people form at once a deep attachment based on common ideals. A lasting friendship developed. We sat in the garden with our home-made telescopes and observed with something near to ecstasy . . . comparing what each of us saw . . . It was wonderful . . . Already at that time Guthnick planned all his observations in the characteristic manner of his later life, and did not simply observe anything and everything that came along, the possible and the impossible, as I did . . . ".

For the first two years of his astronomical career Guthnick joined Professor A. v. Auwers as an Assistant at the Berlin Observatory. After 1903 he worked for three years at the Bothkamp Observatory near Kiel. In 1906 he returned to Berlin as Observer, became in 1916 Professor at the Berlin University, and succeeded in 1921 Professor Hermann Struve as Director of the new Observatory at Berlin–Babelsberg.

His first publication, a note on a variable star in *A.N.*, **155**, 378, pointed the way to one of his main life interests. Shortly afterwards an extension of his thesis was published in the *Nova Acta* of the Leopoldina Academy in Halle under the title "Neue Untersuchungen über Mira Ceti" (1901) and became one of the standard works on this subject.

About 1912 Guthnick's attention was attracted by the progress of the work of the physicists Elster and Geitel, who had brought photoelectric measuring methods to such a perfection that their application to astrophotometry appeared

hopeful. Guthnick succeeded in building a first photoelectric stellar photometer, attached to the Babelsberg 31-cm. refractor, which enabled him to measure stars down to the 8th magnitude. His pioneer work and that of J. Stebbins in Urbana and of H. Rosenberg in Tübingen paved the way to the developments which guided stellar photometry into a new phase.

In 1913 he published in *A.N.*, **196**, 357, a photoelectric study of β Cephei, which was soon, thanks to the very active collaboration of Professor R. Prager, extended to numerous variables, spectroscopic double stars and planets in Vols. **1** and **2** of the *Veröff. d. Sternwarte Babelsberg* (1914 and 1918). Further interesting papers by Guthnick on this development are to be found in *Zeitschr. f. Instrumentenkunde*, **44**, 1924; *Seeliger-Festschrift*, 1924; *Nordisk Astr. Tidskrift*, **7**, 1926; *Himmelswelt*, **39**, 1929, and in *Sitzungsberichte d. Akad. Berlin* of 1924, 1927 and 1930. In these papers we find also photometric studies of the satellites of Jupiter, of the extinction effects and a description of the extension of the photoelectric work to the 125-cm. reflector. Guthnick's earlier photometric work contributed investigations of Eros, Mars, Saturn's satellites and Nova Aquilae 1918. In 1923 he published in the *Atti Pontificia Accad. Rome* an interesting study on peculiar spectroscopic binaries.

Fundamental work concerned the first determination of photoelectric colour-indices (*A.N.*, **210**, 1920), which was afterwards modified and extended by K. F. Bottlinger to his well-known list of 459 stars in *Veröff. Babelsberg*, **3**, 4, 1923, and in a certain way led to the recent important developments of the subject by W. Becker.

Guthnick's work in connection with the Astronomische Gesellschaft Commission for Variable Stars is dealt with in the *Vierteljahrsschrift* of the A.G., particularly since Vol. **59**, and also in the *A.N.* in most volumes since Vol. **223**.

Guthnick's original and often unorthodox outlook was reflected in theories he put forward for several classes of variable stars, e. g. for Cepheids in *Veröff. Babelsberg*, **2**, 3, 1918; *Naturwissenschaften*, **6**, 1918 and *A.N.*, **208**, 1919; and for Mira-stars in *A.N.*, **209** and **210**, 1919.

Mention should be made of Guthnick's well-known contribution "Physik der Fixsterne", which appeared in the encyclopaedic handbook *Kultur der Gegenwart* (Teubner, Leipzig, 1921) and which at the time formed one of the first really modern and comprehensive accounts of the new astrophysics.

In recent years Guthnick's published work mainly appeared in the *Sitzungsberichte* of the Berlin Academy. Here we find the papers on the application of short-focus lenses in astronomy (1926), plans for a new Observatory in Windhuk (1930), and a series of most careful photometric and spectroscopic studies of variable stars with exceptional properties like H.D. 185936 (1930), Zeta Aurigae (1932 and 1935; this in conjunction with work done by Bottlinger, Schneller and Hachenberg), and V 389 Cygni (1937, 1939 and 1942), a very complex system with apparently two superimposed Delta Cephei effects. Guthnick's last paper, written jointly with H. Harting, "Lichtelektrisch-photometrische Untersuchungen", was published by the Berlin Academy in 1944. The problems offered in these recent papers and the methods of attack are in many respects characteristic of Guthnick's whole life-work.

Many honours were conferred upon Guthnick. He became a Member of the Prussian Academy of Science in Berlin, the Bavarian Academy in Munich, and the Leopoldina Academy in Halle. He also was made a Member of the

Pontifical Academy of the Vatican in Rome, with which as an ardent Catholic he had many ties. He was also very actively engaged in the organization of the Astronomische Gesellschaft, to whose Council he belonged since 1924.

He was always friendly and helpful, and he would find at any time a smile or a joke of encouragement for his co-workers and students. He led a happy family life: married in his 45th year to Mrs Melitta Greim, *née* Lang, he had two sons, Ernst and Klement.

Guthnick seemed always of robust health and to his colleagues at the Observatory he appeared full of life and untiring energy. However, an incurable illness compelled him to go to hospital in 1947, but the disease had already developed too far for the operation by the leading Berlin surgeon to be successful.

The heavy loss which science has suffered was expressed by Professor H. Kienle, the present Director of the Potsdam Observatory, in the words in which he announced Guthnick's death to his astronomical colleagues and friends all over the world: "Astronomy loses in Guthnick one of its great representatives, whose memory will remain dear to all who ever came in touch with him".

He was elected an Associate of the Society in 1927 June 10.

A. BEER.

SVANTE ELIS STRÖMGREN was born on 1870 May 31 in Hälsingborg, Sweden and died at the "Rigshospital" in Copenhagen, Denmark, on 1947 April 5. He was a student at the University of Lund from 1887 to 1898. In the last year he received his Ph.D. degree by publicly defending his earlier published thesis: "Bestimmung der Bahn des Kometen 1890 II" (Lund 1896). In the same year he was appointed Lecturer (Docent) at the University of Lund. In the year 1901 he started work as Assistant at the Editing-Bureau of *Astronomische Nachrichten* at Kiel, Germany, and remained in that position until 1907. In the year 1904 Strömgren was appointed *Privatdozent* at the University of Kiel. In 1907 he became by Royal appointment professor at the University of Copenhagen and director of the Royal Observatory at that city. He resigned from these positions in 1940 and was succeeded by his son, Dr Bengt Strömgren.

In his thesis Strömgren performed a thorough and considerable work of computation. The definitive orbit of the Comet 1890 II was derived on the basis of 899 observations of the coordinates of the comet. At the end of the paper the author pointed out that the hyperbolicity found ($e = 1{\cdot}0004103$) did not represent the actual eccentricity. The elements derived by the usual methods are *osculating*, which means that they define the orbit the comet should take if at a given moment the planets should be annihilated and the comet from that moment was subject only to the gravitation of the Sun. By deriving the osculating eccentricity for epochs backwards, from 1890 to 1886, it was found that e decreased and it was correctly concluded that the hyperbolic character of the orbit must be entirely illusory. The thesis ends with the suggestion that e, by further backwards-computing, might turn out to be smaller than one.

The first person to make a backwards-computation of e seems to have been Carl Anton Thraen, who, in a paper published in 1894 (*Astronomische Nachrichten*, **36**), found that the osculating eccentricity of the Comet 1886 II decreased from $1{\cdot}000228$ for the epoch 1885 December 8 to $1{\cdot}000002$ for the epoch 1882 October 5.

In three subsequent papers published at Lund 1898–99, Strömgren further developed his enquiries into the problem as to the "original eccentricities" of

comets, that is to say the value of e when the perturbations are computed from the epoch of osculation until an epoch when the planetary perturbations work in such a way that the conditions of the two-bodies problem are fulfilled in practice. His work in this domain culminated with the paper: "Über den Ursprung der Kometen", written with essential help of Mag. Sc. Johannes Braae.

In this important paper, methods are developed for the backwards-computation of e. The values of the eccentricity are derived with regard to the centre of gravity of the perturbing bodies.

To the undisturbed coordinates (x_0, y_0, z_0) and the velocities $(dx_0/dt, dy_0/dt, dz_0/dt)$ are added the perturbations ξ, η, ζ ; $d\xi/dt, d\eta/dt, d\zeta/dt$, as well as the coordinates and velocities $\xi_\odot, \eta_\odot, \zeta_\odot$; $d\xi_\odot/dt, d\eta_\odot/dt, d\zeta_\odot/dt$, respectively, derived with regard to the gravity centre of the planetary system.

Up to 1944 the methods developed in the said paper have been applied to altogether 21 comets. With regard to the general interest connected with these results, based on long and tedious computation work and careful reduction of observations of cometary positions, we quote here the results as to the values of e, taken from the well-known Norwegian textbook: "Laerebog i Astronomi", originally written by H. Geelmuyden at Oslo, Norway, and revised and rewritten by Elis and Bengt Strömgren.

No.	Comet	Osculating e	Osculating $1/a$	Mean error	Original $1/a$
1	1853 III	1·000 2514	−0·000 8193	±0·000 0228	+0·000 0829
2	1863 VI	1·000 6499	−0·000 4949	0495	+0·000 0166
3	1882 II	0·999 9078	+0·011 8963	2710	+0·012 1488
4	1886 I	1·000 4461	−0·000 6944	0220	−0·000 0071
5	1886 II	1·000 2286	−0·000 4770	0091	+0·000 3166
6	1886 IX	1·000 3824	−0·000 5765	0276	+0·000 0630
7	1889 I	1·001 255	−0·000 6915	0606	+0·000 042
8	1890 II	1·000 4103	−0·000 2151	0101	+0·000 0718
9	1897 I	1·000 9270	−0·000 8722	0476	+0·000 0396
10	1898 VII	1·001 0336	−0·000 6074	0096	−0·000 0157
11	1902 III	0·999 9675	+0·000 0810	0184	+0·000 0054
12	1904 I	1·001 3646	−0·000 5040	0079	+0·000 2165
13	1905 VI	1·000 1846	−0·000 1424	0501	+0·000 6210
14	1907 I	1·001 024	−0·000 4991	0400	+0·000 0252
15	1910 I	0·999 9723	+0·000 2143	1479	+0·003 3021
16	1914 V	1·000 1618	−0·000 1465	0031	+0·000 0119
17	1922 II	1·000 8596	−0·000 3806	0174	+0·000 0038
18	1925 I	1·000 6286	−0·000 5665	0310	+0·000 0540
19	1925 VII	1·000 4276	−0·000 2730	0226	+0·000 1150
20	1932 VI	1·001 3760	−0·000 5948	0010	+0·000 0441
21	1936 I	1·001 97	−0·000 487	±0·000 22	+0·000 205

It is clear from the table above that the backwards-computation has in 20 out of 21 cases transformed the orbit into the elliptical direction. There are two cases when there is a small hyperbolic eccentricity left, but we have to remember that the values of $1/a$ must be considered as illusory when due regard is taken of the size of the mean errors. Further, it should be remarked that the values of e on an average certainly would be shifted in the elliptical direction if the perturbations of Uranus and Neptune had been taken into account.

It means no restriction in the appreciation of the important contribution to the problem of the origin of the comets here reviewed if the present writer declares that he is of the opinion that the results given above cannot be considered as definitely proving that all comets belong to our solar system. There are several results from statistical inquiries which suggest that there may also be comets which wander from one stellar system to another stellar system.

Another main piece of work by E. Strömgren is his numerical integration of orbits in the extended *problème restreint*. In the cases considered, two of the masses (m_1 and m_2) are equal and the third is considered as infinitely small in comparison with the two others. The system of coordinates is taken so that one of the axes goes through the line connecting m_1 and m_2, and the axes rotate uniformly with the said line. The problem is then to find the orbits of a particle near to, or at a considerable distance from, one of the five libration-points of Lagrange.

The second part of the problem was first formulated by Thiele and investigated by him in cooperation with C. Burrau and N. P. Bertelsen. The first two named found a solution for the point L_2 and proved the existence of periodic orbits around this point. There were also found so-called ejection-orbits (orbits for ejected or falling-in particles).

The extensive numerical integration work performed under the guidance of E. Strömgren during more than three decades at the Royal Observatory of Copenhagen has led to an interesting classification of the *single periodic* orbits in the extended *problème restreint*.

Classification of the orbits

a. Periodic orbits around the point L_2 ("Librations" around L_2).
b. Periodic orbits around the point L_3 ("Librations" around L_3).
c. Periodic orbits around the point L_1 ("Librations" around L_1). When $m_1 = m_2$, L_1 is situated halfway between the two masses and the librational movements are symmetrical with regard to the η-axis.
d. Periodic orbits around the point L_4 ("Librations" around L_4).
e. Periodic orbits around the point L_5 ("Librations" around L_5).
f. Retrograde periodic orbits around m_2.
g. Direct periodic orbits around m_2.
h. Retrograde periodic orbits around m_1.
i. Direct periodic orbits around m_2.
k. Direct periodic orbits around the two finite masses m_1 and m_2.
l. Retrograde periodic orbits around the two finite masses but direct motion in the absolute system of coordinates.
m. Retrograde periodic orbits around the two finite masses but retrograde motion in the absolute system of coordinates.
n. Retrograde periodic orbits reminiscent of the librational orbits around L_1. In this case there is no symmetry with regard to the η-axis.
o. Retrograde periodic orbits also of the same kind as in the foregoing case and also unsymmetrical with regard to the η-axis.
p. and *q*. The orbits found by Darwin having the ∞-form. The orbits wind themselves around m_2 and L_2 or m_1 and L_3, respectively.
r. and *s*. Groups of periodic orbits related to the groups *k* and *l* and like these related to certain periodic orbits ending asymptotically in one of the libration-points.

More than fifty computers have taken part in the numerical derivation of the orbits. Already in 1923 the number of computed orbits was 506. In future the services of the wonderful computing machines constructed during the second world war no doubt will be used for problems of the kind here considered. But that will by no means lessen the value of the pioneer work by E. Strömgren and his co-workers.

In connection with the investigations on the extended *problème restreint* a solution was found giving periodic orbits for the mass values : $m_1 = m_2 = 1$ and $m_3 = 2$. Also ejection orbits were discovered in this case. Finally the computation of orbits within a globular cluster should be mentioned.

A rather complete bibliography of the writings of E. Strömgren has been given by the present writer in the celebration volume : "Astronomical Papers dedicated to Elis Strömgren", Copenhagen 1940. The "main series" in this bibliography gives 156 items. To this is added a long list of observations, orbital elements and notes concerning comets and small planets, observations and notes as to variable stars, occultations and eclipses. Furthermore, there are many literary reviews, obituaries and papers and notes concerning matters of organization.

E. Strömgren was an able mathematician and well trained in the classical branches of celestial mechanics. He had a wide knowledge and experience in spherical astronomy, astrometry and numerical computation. Like many of his generation he held, especially so in earlier days, a rather sceptical attitude towards the modern branches of astronomy. But he was by no means the worst of the backsliders. By and by, he gave in and admitted the importance of advances within stellar astronomy and astrophysics won during the last decades.

As a teacher and examiner he was clear and concise. He was a very good editor. His criticisms, advice and suggestions always were excellent and the author had only to accept them gratfully. From what has been told above it should be quite clear that E. Strömgren was a great organizer.

These lines would be very incomplete if they did not say a few words as to his highly appreciated work for keeping up the relations between astronomers in different countries and also the distribution of astronomical news during the two world wars. In *Astronomische Nachrichten*, **109**, 333, 1914, there is a communication to the effect that the bureau at Kiel for distribution of astronomical news could not continue its activities and that E. Strömgren had undertaken the news distribution. Intentionally it was the distribution of telegrams that was placed at Copenhagen, but eventually the Copenhagen Observatory developed into an actual astronomical centre showing numerous activities and doing contemporary astronomy many valuable services. In *Astronomische Nachrichten*, **211**, 15, 1920, the leading German astronomers expressed their gratitude and appreciation of the work E. Strömgren had performed for creating goodwill and understanding between different nations. In 1922 under the auspicies of the I.A.U. the *Bureau Central Astronomique* was founded at the Royal Observatory of Copenhagen. The first circular of that Bureau dates 1922 October 22 and up to date some 1140 Circulars have been published. Strömgren took a very active part in the work of the Bureau, even after his resignation. These Circulars form a very valuable source for observations, especially within the astrometric branch of astronomy. During the second world war the distribution of astronomical news could be kept up in a rather satisfactory way, although the difficulties were considerable, owing to Denmark being invaded and occupied by the Hitlerian forces in 1940.

The interest taken by Strömgren in international relations between astronomers made the Copenhagen Observatory an international astronomical centre. Much hospitality was shown by Dr and Mrs E. Strömgren at their home at Östervold (Eastern Wall) and several astronomical congresses and meetings were held in the Danish capital, and Strömgren and his family took an active part in all of these meetings.

Strömgren was president of the society *Astronomische Gesellschaft* during the years 1921–1930 and directed the meetings in Potsdam 1921, Copenhagen 1926, Heidelberg 1928 and Budapest 1930. He was a member of several commissions of the I.A.U.

Strömgren was a member of a good many scientific societies and received several distinctions. He became an associate of this Society on 1916 June 9, and he was a member of the Royal Swedish Academy of Science, and further, of the Danish, Finnish, Norwegian and Prussian Academies of Science. In 1928 he was created Dr. Phil. *honoris causa* at the University of Greifswald. He was in 1933 elected member of the American Museum of Natural History at New York. In 1923 he declined to accept the Chair of Theoretical Astronomy at the University of Berlin and the directorship for the Astronomical Recheninstitut at Berlin-Dahlem.

The strong interest taken by Strömgren in the contemporary personal history of astronomy branched out also in an interest in several questions within the vast domain of the earlier history of astronomy. Strömgren devoted a good deal of time in the work for the preservation of the ruins of the two observatories of Tycho Brahe at the island Hven, namely Uraniborg and Stjärneborg. He also contributed papers concerning Tycho Brahe and Ole Rømer. Together with Dr Bengt Strömgren and Dr Hans Raeder he published in 1946 a translation into English of the description of the instrument and astronomical work that Tycho Brahe has given in his famous and now rare work : "Astronomiae Instauratae Mechanica etc." of 1598 and 1602. In 1944 Strömgren published an extensive paper dealing with Ole Rømer, his personal history and scientific achievements.

Finally, brief mention should be made of the interest taken by Strömgren in popular and pedagogic astronomical literature and his many contributions within that branch. His gift for matters of organization was amply applied to the leadership of the Northern Astronomical Society (Nordisk Astronomisk Selskab) from 1920 to his death and the editing of the *Northern Astronomical Journal* (*Nordisk Astronomisk Tidsskrift*) during the same time. As one of the many activities shown in connection with this work may be mentioned the organizing jointly with Axel V. Nielsen at Aarhus of the vast series of observations of variable stars, performed by Danish and Swedish amateurs.

In 1902 he married Hedvig Lidforss, daughter of Professor V. E. Lidforss of Lund, the well-known dentist and literary and scientific author, and had two sons. The older is his successor, the well-known astronomer Dr Bengt Strömgren and the younger is the well-known Professor of Psychiatry at Aarhus, Dr Erik Strömgren.

KNUT LUNDMARK.

LUDWIG BECKER was born at Wesel on 1860 January 8. From local schools he went to the "Realschule" at Münster and then for a short time to Berlin University where he studied mathematics and physics. From 1879 to

1881 he studied at Bonn specializing in astronomy. He was awarded the Ph.D. degree in 1882 for the calculation of the general perturbations of the minor planet (72) Feronia.

On leaving the University he was employed by the *Berliner Jahrbuch* and took a considerable part in the calculations of the motions of the minor planets. Overwork was followed by a serious illness and on medical advice he accepted a post at Lord Crawford's observatory at Dunecht, Aberdeenshire, in 1885. There he threw himself into observational astronomy, observing nebulae and other objects with the transit circle and making spectroscopic observations with the 15-inch refractor. For three summers he observed the spectrum of the Sun near sunrise and sunset from the Barmerkin of Echt—a hill about a mile and a half from the observatory. For this work he was awarded the Makdougall-Brisbane prize of the Royal Society of Edinburgh.

In 1888 Lord Crawford offered his instruments and library to the Royal Observatory, Edinburgh, and this offer was accepted. Early in 1889, Dr Copeland, the Director of Lord Crawford's observatory, was appointed Astronomer Royal for Scotland and Becker became a temporary assistant at the Royal Observatory. Much of the preparations for moving the instruments from Dunecht to Edinburgh fell to Becker and in particular he was responsible for adjusting the piers to support the Transit Circle. While the work was still in progress he was appointed Regius Professor of Astronomy at Glasgow—a post he held for the next 42 years.

His first task at Glasgow was the renovation of the instruments. For this work he was fortunate in receiving a grant of £1000 from the Bellahouston Trustees. The 6-inch Ertel Transit Circle was reconditioned and the 20-inch Bredalbane Reflector was overhauled and provided with a large spectrograph, a really powerful instrument for that time. He started observing as soon as the instruments were ready. With the transit circle his programme was to observe stars close to the pole and in particular two faint stars so close to the pole that they were always within the field of view of the telescope. By observation of the same stars at intervals of several hours he was able to determine the position of the pole relative to the instrument and then accurate positions of the stars. His intention was to determine accurately the constants of nutation and aberration. Although hampered by the unsuitable climate and the neighbourhood of a large industrial city, he carried on the observations single-handed for 10 years and the results are published in the *Memoirs*, **62**, 49. With the spectroscopic observations weather was also a most disturbing factor but very long exposure spectrograms were made of a number of objects, e. g. novae, comets and nebulae. Spectra of the major planets were also photographed. Some results were published in the *Monthly Notices*.

Professor Becker early made the acquaintance of Franklin Adams and was of some assistance to him in setting up his instruments at Machrihanish. Becker and Franklin Adams observed the total eclipse of 1905 August 30 in Tunis and Becker's photometric observations of the corona were published in the *Transactions of the Royal Society of London*.

When Becker returned to the observatory after the 1914–18 war he was too old to undertake regular night observing in addition to his day duties. His activity, however, is only partly shown by a number of papers. These may be divided into two series. The first deals with mechanical contrivances, such as

the construction of a motor micrometer for the transit circle and an artificial horizon to be attached to sextants for use at sea or in aircraft. The second series deals with computations—he was a master computer—especially those of gravitational problems for which a solution could only be obtained by mechanical quadrature.

Becker will be long remembered amongst Glasgow students for the lectures which he delivered throughout his long tenure of office. For most of the time he must have had larger classes than any other professor of astronomy in Great Britain. The lectures did not concern popular or descriptive astronomy but were on spherical and dynamical astronomy. He gave a sound theoretical development of the subject and carried the analysis to the limits of practical usefulness. Students had to compute the actual ephemeris of a planet from the orbital elements. In practical astronomy they had to learn to observe with various instruments and to determine clock error, latitude and azimuth. (He had long hoped that his lectures on spherical astronomy might be published, but the high cost of reproducing the many diagrams which are so important in helping the student has so far prevented publication.)

He was a most approachable professor and easily made friends with his students. Soon after the commencement of term he used to give the students a key to the observatory and tell them that the observatory was open from "noon till noon"—the limits of the astronomer's day before 1925. The writer remembers how 40 years ago when talking to Becker about Bessel Functions he said—"There is nothing difficult about these functions. When you come to a differential equation you can't solve or an integral you cannot evaluate in terms of known functions you just invent a new one and proceed to calculate its value".

Becker married in 1900 and is survived by his widow, four of their five children and eight grandchildren. His life was a happy one till the war of 1914–18. He had long been a naturalized British subject but all his relatives were in Germany and as a result of local agitation he was compelled to leave Glasgow for a considerable period. After that war his wife and family spent most of their time in Germany but he, for financial reasons, carried on at his old post and it was only in 1935 that he retired. For the remainder of his life he and his wife lived at Lagundo in northern Italy. His latter years were saddened by the second world war and with anxiety about his children. Nevertheless, in spite of his great age, he remained mentally and physically active till the end of 1946, working away at astronomical problems and preparing his lectures for publication. In the last year of his life there were definite signs of his heart failing and he required medical attention, although he rallied more than once. The end came on 1947 November 11, when he died at Lagundo in the presence of his wife, all his children being separated from him by closed frontiers.

He was elected a Fellow of the Society on 1893 April 14. He was not in fact a Fellow at the time of his death, having resigned in 1946. But in view of his long-standing membership and of his services to astronomy, the Council desires this record to appear in these pages.

J. JACKSON.

(Abstracted in large measure from the *Proceedings of the Royal Society of Edinburgh*, by kind permission of the Editors.)

GODFREY HAROLD HARDY, the celebrated pure mathematician, was born on 1877 February 7, the son of Isaac and Sophia Hardy, of Cranleigh, Surrey. He was educated at Winchester and Trinity College, Cambridge, going up to Cambridge with an Entrance Scholarship in 1896 and reading mathematics. He was placed fourth Wrangler in the Mathematical Tripos of 1898, and obtained a first division in the first class of Part II of the Mathematical Tripos of 1900. He was awarded a Smith's Prize, in company with Jeans, in 1901. In 1900 he was elected to a Prize Fellowship at Trinity; from that time on, he devoted himself to research in pure mathematics. In 1906, when his Prize Fellowship was due to expire, he was put on the Trinity staff as Lecturer in Mathematics, a position he continued to hold until 1919. He was elected a Fellow of the Royal Society in 1910. The University of Cambridge recognized his world-wide reputation as a researcher in the theory of the real and complex variables, and in the theory of numbers, by giving him the honorary title of Cayley Lecturer in 1914. In 1919 he was elected to the Savilian Chair of Geometry in the University of Oxford, with a Fellowship at New College. He respected the title of his Chair to the extent of giving certain lectures in geometry, but in the main he continued his previous interests, though occasionally lecturing on mathematical philosophy for non-mathematicians. For 1928–1929 he was a Visiting Professor at Princeton, N.J., and at the California Institute of Technology, O. Veblen coming to Oxford in his place. In 1931 he returned to Cambridge to succeed E. W. Hobson in the Sadleirian Chair of Pure Mathematics, being re-elected to a Fellowship at Trinity. He was later elected to an Honorary Fellowship at New College, an honour of which he was very proud. He held honorary degrees from Athens, Harvard, Manchester, Sofia, Birmingham, Marburg and Oslo. He was awarded the Royal Medal of the Royal Society in 1920, its Sylvester Medal in 1940 and the de Morgan Medal of the London Mathematical Society in 1929. He was President of Section A of the British Association at its Hull meeting in 1922. He was President of the National Union of Scientific Workers in 1924–26. He was long associated with the London Mathematical Society as member of Council and Secretary, and he had the unusual distinction of being twice President, namely for 1926–28 and for 1939–41. He was an honorary member of many of the leading foreign scientific academies. He retired from the Sadleirian Chair in 1942, and died on 1947 December 1, the day on which the Copley Medal of the Royal Society—its highest award—was due to be presented to him.

Such are the bare formal details of Hardy's life and distinctions. Why are these important for astronomers? Because Hardy was a mathematician who profoundly influenced mathematics in this country, who gave it standards of rigour in which, before him, it had been sadly lacking, and through whose hands passed many of those who were later to become well-known mathematical astronomers. His book, "A Course of Pure Mathematics", first published in 1908, went into edition after edition; generations of undergraduates, in universities the wide world over, were brought up on it; and to those who had the privilege of attendance at his lectures on analysis and the theory of functions, he was the very voice of inspiration, to many indeed a personal friend. But Hardy was much more than a teacher and researcher of international fame. He was a personality—one might truly say the leading personality in the English mathematical world—who radiated an attitude to mathematics which made it

shine as something supremely worth while, something clean and clear and bright and universal (as the Warden of New College has written), something fundamental to the living of the good life, and that the more so the less its utilitarian applications. Some of these feelings about pure mathematics he gave expression to in his "A Mathematician's Apology", but Hardy the man was again something greater even than his fastidious literary style conveyed. His conversation on all subjects was gay, provocative, fascinating; on mathematics inspiring; on cricket encyclopaedic; even on astronomy (of which he affected to be ignorant) knowledgeable and stimulating; on all topics entertaining. Without ever seeking it he was the recipient of much affection and much secret hero-worship. He was through and through intellectually honest; he was youthful in outlook to the day of his death. Though his attitude to religion shocked many people—his Polish pupil Zygmund used to say that Hardy was the only man he had ever known who took God for his personal enemy—yet Hardy's deep reverence for mathematics and for all things of the mind was precisely of the same kind as impels other people to the worship of God; the only enigma about Hardy was that this never seemed to occur to him.

It was at one time said in Trinity that Hardy was a fighter for lost causes. One cause he fought for supremely successfully—the battle for the reform of the old Mathematical Tripos Part I and the abolition of its order of merit. Hardy was an able pamphleteer, and one of his fly-sheets in that controversy claimed that a certain specified number of members of the Cambridge Senate "with mathematical degrees" were in favour of the reform. This number was disputed by the other side, and when Hardy came to verify it, great was his chagrin when he found that he had erroneously reckoned himself as possessing a "mathematical degree", whereas having taken the Tripos at the end of his *second* year he had proceeded to his B.A. at the end of his third year on the strength of a certificate of diligent study only, thus counting as the possessor of a mere poll degree, which did not rank for subject. But still greater was his joy when he was able to restore the number of his supporters to its original figure, by counting in, as the possessor of a mathematical degree, the venerable classic, H. Montagu Butler, the Master of Trinity, who in remote ages had actually taken the mathematical tripos. This little story, which I had from Hardy himself, well illustrates the attractive whimsicality of his character, and his zest for the odd things of life and learning.

I have indicated that his direct connection with astronomy was slight. He actually became a Fellow of the Royal Astronomical Society in 1918 at the time of the great debates between Eddington and Jeans, doing so in order to be able to attend the debates personally. The writer well remembers one later occasion of a similar character when Hardy took an effective part in a Royal Astronomical Society debate—the debate of 1930 December 12, on the subject of stellar structure—when in addition to several other speakers R. H. Fowler was presenting a paper on Emden's and allied differential equations. Hardy seriously discussed Fowler's contribution, but concluded by remarking that of one thing (amidst so much that was the subject of dispute) he was sure, and that was that Fowler's work on Emden's equation, being pure mathematics, would retain its value long after all the various *physical* theories of the internal constitution of the stars had become obsolete—a prophecy which has in a fair measure been fulfilled.

The writer, though an undergraduate pupil of Hardy's, was never one of his research pupils. But he had the great privilege of knowing Hardy well, both in his Cambridge and Oxford settings. He can bear witness to the fact that after Hardy's social discomforts at the High Table of Trinity, Hardy expanded and mellowed in a wonderful way, in what was to him the more benign atmosphere of New College. His popularity there was immediate and assured, and he gave back in the intellectual exhilaration of his conversation what he received in sympathetic friendship. By the time of his return to Trinity his formerly lost causes had all been won, and he enjoyed his return. He once remarked that his Prize Fellowship at Trinity was the most important event in his academic career.

For many of the band of mathematicians—in Britain, on the Continent and in America—Hardy's death extinguished one of the lights of our lives.

He was elected a Fellow 1918 June 14.

E. A. MILNE.

EDWIN THOMAS HOLDAWAY was born in Brisbane in 1895. By profession a surveyor since 1912, he was appointed Assistant Astronomical Observer in 1929 and Officer-in-Charge, Cartographic Branch, Brisbane, in 1940. His interest in astronomy was largely responsible for the foundation in 1927 of the Astronomical Society of Queensland. It was also largely due to his enthusiasm and that of a few friends that this centre of astronomical activity was steered through a period of low ebb when local interest flagged. He served as Secretary of that Society for ten years, was several times President and was Librarian at the time of his death at Brisbane on 1947 February 14.

He was married in 1919 and is survived by his widow and two daughters.

He was elected a Fellow of the Society on 1938 January 14.

HENDEN EGERTON HOUGHTON was born in London on 1892 February 25, and died in Johannesburg on 1947 December 15. He was educated at Whitgift School, Croydon, and from there followed his father into the Civil Service. Beginning in one of the Post Office Departments, he was later transferred first to the Customs and Excise Division and later to the Colonial Office (now the Dominions Office) in Downing Street. It was there, due to long hours and overwork during the 1914–18 war, that his health broke down and he contracted the crippling arthritis from which he was to suffer for the rest of his life. After a period of sick leave the Colonial Office arranged for his transfer to the High Commissioner's Office in South Africa, in the hopes that the warmer climate might suit him better. Accompanied by his mother he left England in the early winter of 1920 and made his home in Cape Town, though his time was about equally divided between Pretoria and Cape Town as the Parliamentary Sessions opened and closed. In 1943 he married Miss Zeta W. Burgess of Johannesburg, with whom he enjoyed a happy married life. After some months of increasing ill-health he retired on pension early in 1947 and settled in Johannesburg, but unfortunately he was spared for all too short a time to enjoy his well-earned leisure. In recognition of his many years of devoted service to the High Commissioner's Office he was awarded the M.B.E. in 1937.

Houghton became interested in astronomy while still a young man and on arrival in South Africa got in touch with the very keen and capable group of

amateurs centred in Cape Town. He quickly became one of the most active members of the Variable Star group and became its Director on the retirement of Mr G. E. Ensor in 1934. His astronomical outlook and achievement are perhaps best told in his own words taken from his Presidential Address to the Astronomical Society of South Africa delivered in July 1937.

> " I need not stress the goodwill between the professional and the amateur in astronomy—the only limits to a complete entry by the amateur into all the mysteries are lack of training, time and equipment. These, you will say, are serious drawbacks, but they can largely be overcome given an aptitude and sufficient application. One of the secrets is to specialize. It may seem ambitious for a beginner to think of specializing in one branch of astronomy, but the limitation of time and equipment can best be got round by so doing; otherwise time is wasted and equipment imperfectly used.
>
> This brings me to my subject: the observation of Long-Period Variable Stars. I was introduced to this branch of astronomy when I joined the Cape Astronomical Association, the forerunner of this Society, in 1921. Equipment and time were limited and training had to be acquired. Since that date I may say, for the encouragement of others of equally limited opportunity, that I have made some 20,800 observations of a list of stars now totalling 90 from which it has been possible to deduce about 760 maxima and 640 minima . . . . ".

This observational achievement would be remarkable for a man in possession of all his faculties, but for a man crippled as Mr Houghton was, it is surely a triumph of grit and determination. At first he used quite a small telescope but later assembled a larger telescope for himself, the tube being made to his orders by a local firm of metal workers, who sent in a bill for " one stove-pipe ". It was in Cape Town while observing a variable star in Apus that Houghton discovered Comet 1932b (Houghton-Ensor), which was discovered independently by his fellow variable star observer G. E. Ensor at Pretoria on the following evening.

Variable stars were his chief interest, but his wide reading and extensive study made his carefully prepared talks a joy to listen to; while his contributions to the Journal and later to the Monthly Notes of the Astronomical Society of South Africa make useful and delightful reading at any time and are of lasting interest. He was Secretary of the Astronomical Society for seven of its most successful years and was elected its President in 1936. As a member of Council his cheerfulness, ready wit and sound good sense were a constant tower of strength. The following words taken from the Session Memorial Minute of the Gardens Presbyterian Church, of which he was an Elder, sum up the impression of those who knew him best:

> " Houghton was a man of deep and quiet piety, a generous and kindly personality, faithful, wise and good. In particular we honour him for his invincible spirit and wonderful cheerfulness in the face of crippling disease . . . . ".

He was elected a Fellow of the Society on 1930 May 9.

R. H. STOY.

WILLIAM MACINTYRE was born in Peebles in 1875. He was trained as a mechanical and electrical engineer, first in the workshop and later at the

Heriot Watt College, Edinburgh. His first employment was in the drawing-office of a firm of electrical engineers, where he attained the position of chief draughtsman. He afterwards held a responsible post with the British Westinghouse Company, of Manchester, his work being mainly concerned with electrical design. Finally, shortly after the first World War he came to live in Harrow and set up as a consulting engineer in Victoria Street, Westminster. He had retired from active professional work some time before 1939, but undertook important work for the Admiralty during the war years. He died on 1947 May 2.

MacIntyre will chiefly be remembered among astronomers for his skill in the figuring of optical surfaces. He made and mounted equatorially an excellent 10-inch reflector and had also finished a 15-inch mirror some years before his death, though he never actually mounted it. In addition he made a large number of circular planes, for himself and his friends, and he also made and presented to the British Astronomical Association a 4-inch objective prism of flint glass. All this work was carried out, in the attics of his house at Harrow, with the same neatness and accuracy that characterized his thought, speech and writing. The lucidity and legibility of his letters will be specially remembered by the many amateur workers who are indebted to him for help and advice that was always freely given, while those who were privileged to know him personally will have happy recollections of the brisk cheerfulness of his speech and manner.

He served as Treasurer of the British Astronomical Association from 1936 to 1939, and as Secretary from 1939 to 1945, being Vice President from 1945 to the date of his death.

MacIntyre, whose wife's death in 1945 was a great grief to him, leaves two sons and a daughter. He was elected a Fellow of the Society on 1935 May 10.

W. H. STEAVENSON.

ANNIE SCOTT DILL MAUNDER was a professional astronomer before she married, for in 1891 she and three other young women were appointed "Lady Computers" at the Royal Observatory, Greenwich, and part of her work there was to examine and measure the daily sunspot photographs.

Her maiden name was Russell. She was born in 1868 in County Tyrone, Ireland, and educated in Belfast and Girton College, Cambridge, being Senior Optime in the Mathematical Tripos in 1889. In 1892 she received the special invitation, shared by very few other women, to attend all ordinary meetings of the Society, and in 1916 she was elected a Fellow.

Her work on sunspots led naturally to her friendship with Edward Walter Maunder, head of the Photographic and Spectroscopic Department in Greenwich Observatory, and also to interest in the British Astronomical Association, which he had founded in 1890: she helped in many ways in the early times of the Association, and was for many years Editor of the Journal. In 1895 they were married. Maunder was a widower and father of a family, and he was 17 years older than Annie Russell; but love on both sides was deep and true, and their aims and interests in life were the same.

In astronomy it was an ideal partnership: they wrote many astronomical articles together, signed with both names, and one of Mr Maunder's books is dedicated to "My Wife, my Helper in this Book and in all things". The Sun continued to be a favourite subject with both: they went to five total solar eclipses together, and at one of these, in India in 1898, she secured a photograph of a

longer coronal streamer than had ever been photographed before. It was with this purpose that she had carefully prepared and equipped her instrument. For as well as the help she gave her husband, much of her work was quite original: she had an alert and active mind, and her lively imagination was combined with a tireless zeal in seeking evidence and working out details before presenting any conclusions. In 1907 May her paper on "An Apparent Influence of the Earth on the Numbers and Areas of Sunspots in the Cycle 1889–1901", which was based on a study of Greenwich Results for these twelve years, was published in *Monthly Notices*, being communicated by the Astronomer Royal; in the same month she gave the gist of this long paper to a meeting of the B.A.A. It is very full and thorough and carefully argued; and although an Earth effect can scarcely be more than "apparent", the fact of a decrease in spot frequency as they pass from east to west of the Sun's disk viewed from Earth has never since been disproved or satisfactorily assigned to any other cause. She showed in the paper that it was very difficult of explanation by a changing presentation of the spots to Earth as they passed over the Sun's disk, also that it was supported by the new fact that spots were more numerous when the Sun was in apogee.

The origin of the 48 ancient constellations was also a very interesting problem to the Maunders. He had discussed it in *The Observatory* and the *Journal of the B.A.A.* and elsewhere, in 1898, stressing the point formerly observed by Proctor that the extreme limit in southern latitude of these figures gives a clue to the latitude of their inventors, and also to the time at which they observed, since the South Pole must then have been at the centre of the circle which surrounds the southernmost of the figures. She carried the argument further in *The Observatory* of 1912 and 1913, and finally in *The Observatory* of 1936 suggesting there that the inventors were some Indo-European race of the late Stone Age who were sailors rather than agriculturists and had domesticated the horse, their date being about 2900 B.C.

In 1928, to her great grief, Mr Maunder died, but she continued her work alone in astronomy and kindred subjects, one of which was chronology: Eddington once referred to her an inquiry on the date of the Nativity, as to an authority on this subject. Only recently did she find it impossible to attend astronomical meetings, or to deal with her many files and notes and letters from correspondents all over the world. Her strength failed and she passed away after a very short illness on 1947 September 15.

She was elected a Fellow of the Society on 1916 November 10.

M. A. EVERSHED.

JOHN ANTHONY MILLER was born in Greensburg, Indiana, on 1859 December 16, and died in his home in Wallingford, Pennsylvania, on 1946 June 15. He had been a country school teacher for several years before he entered the University of Indiana, where he received the Bachelor of Arts degree in 1890. There he came under the influence of a young mathematics teacher, Joseph Swain, who afterwards was to become President of Indiana University, and later of Swarthmore College. It was due to Swain's influence that John Miller went to Stanford University as a member of the Mathematics Department (instructor 1891–1894; assistant professor 1894–1895). After these years in Stanford, John Miller returned to the University of Indiana as professor of mechanics and astronomy, which post he held until 1906. He received the degree

of Doctor of Philosophy in Mathematics from the University of Chicago in 1899, after two years on leave. His Doctor's dissertation had been on the subject of elliptic modular functions, but now his interest shifted to astronomy. He used the 12-inch refractor at Indiana University for the study of double stars; in 1905 he was in charge of an expedition sent by the University of Indiana to observe the total solar eclipse in Spain.

In 1902 Joseph Swain became President of Swarthmore College, which had been founded in 1864 by members of the Society of Friends. In 1906 Dr Susan J. Cunningham, the first Professor of Mathematics and Astronomy at Swarthmore College, retired, after having been connected with the College from 1869. Through the efforts of Miss Cunningham, a small observatory was erected in 1887, containing a 3-inch transit instrument, 6-inch equatorial telescope and other equipment. These various instruments are part of what is now referred to as the Students' Observatory, which is used principally for instructional purposes.

At the invitation of Joseph Swain, Dr Miller came to Swarthmore as Professor of Mathematics and Astronomy. Dr Miller's requirement of a large telescope was fulfilled by the gift made in 1907 by William Cameron Sproul, an alumnus of Swarthmore College and a former pupil of Miss Cunningham. Mr Sproul, who later became Governor of Pennsylvania, provided funds for a visual refracting telescope and additional equipment. The telescope, built by the John A. Brashear Co., was completed in the summer of 1911 and mounted the following December; it has an aperture of 24 inches and a focal length of 36 feet. Dr Miller recognized the value of the large refractor for the problem of determining stellar parallaxes from Frank Schlesinger's pioneer work with the Yerkes refractor. Under Miller's leadership several hundred parallaxes were measured during the next twenty-five years. As time went by, the growing collection of photographs provided a valuable basis for the subsequent study of mass-ratios. Throughout the years Dr Miller had the faithful cooperation of his colleague, John H. Pitman; of the many others working with him, Drs Ross W. Marriott and Michael S. Kovalenko must be mentioned.

In addition, Dr Miller devoted himself to the observation of total eclipses of the Sun, paying particular attention to the structure, state of motion and density of the solar corona. He observed his first eclipse in Georgia in 1900. We have already referred to his 1905 eclipse expedition to Spain. The 1918 eclipse he observed from Brandon, Colorado, the 1923 eclipse from Yerbanis, Mexico. For the 1925 eclipse, the Swarthmore eclipse instruments were located on the grounds of the Yale Observatory in New Haven, Connecticut. The 1926 eclipse was observed from Benkoelen, Sumatra, and he returned to Sumatra to observe the 1929 eclipse from Takengon. His last eclipse expedition was in 1932; the eclipse camp was located near Derby, Vermont. This was his first expedition on which cloudy weather prevented a successful carrying out of the eclipse programme. On all the Swarthmore eclipse expeditions from 1923 to 1932, Dr Ross W. Marriott worked closely with Dr Miller.

From 1906 to 1929 John Miller served as Professor of Mathematics and Astronomy at Swarthmore College. From 1913 till 1929 he was also Vice-President of the College. From 1929 to 1936 he was Director of Sproul Observatory and Research Professor of Astronomy, from 1936 Director of Sproul Observatory and Professor of Astronomy, Emeritus. An important

contribution of John Miller to Swarthmore College was to convince the Board of Managers and the alumni that one of the functions of a professor in a small college was to do research.

In 1929 Indiana University gave the degree of LL.D. to John Miller. In 1915 he was elected to membership of the American Philosophical Society. From 1920 to 1941 he served as Secretary of the American Philosophical Society. Until his retirement from active work in 1942 John Miller remained in close touch with the College, the Observatory and various other activities. He was a regular attendant at the meetings of the American Astronomical Society and served as a member of the Council, as Vice-President and as a representative in the Division of Physical Sciences.

In 1937, on the 25th reunion of the Class of 1912 of Swarthmore College, that group of alumni presented a gift to the College, to be called the John A. Miller Student Loan Fund. Throughout his long career as a teacher, Dr Miller exerted a great influence on the lives of his students.

He was elected a Fellow of the Royal Astronomical Society on 1922 June 9.

PETER VAN DE KAMP.

DAVID BEDELL PICKERING was born in New York on 1873 January 18, and died at East Orange, New Jersey, on 1946 June 13. Although interested in astronomy from an early age and an active observer, it was not until 1914 that he linked up with other amateurs and thereby began a period of astronomical activity which was of very real value to amateur astronomy in the United States. Beginning (and continuing) as a very keen Variable Star observer, he was one of the earliest organizers of the American Association of Variable Star Observers, becoming its first President in 1917. Perhaps his most important contribution to the work of this Association was his organization of the design and production of suitable Star Charts. He aimed at and achieved a very high standard of draughtsmanship and was himself responsible for a large number of the original tracings.

His influence was also felt in a sphere other than the more technical one outlined above and that was in the personal. He was always very keen on bringing together people sharing astronomical interests and it was this trait that made his name familiar to many. The title of a long series of articles in *Popular Astronomy*, "The Astronomical Fraternity of the World", bears witness to this side of his activities.

From the 1928 Meeting of the International Astronomical Union onward he was a member of its Variable Star Commission.

He was elected a Fellow of the Society on 1928 April 13.

W. M. LINDLEY.

ROBERT JOHN STRUTT, fourth Baron Rayleigh. British Science has owed much in the past to men of independent means, inheriting a distinguished position in the country, who have devoted their energies to some branch of knowledge for its own sake. The death of Lord Rayleigh on 1947 December 12 removes from our midst almost the last representative of this invaluable class to whom a university post was an opportunity to work rather than an object of ambition.

The son of one of the most distinguished physicists in England, the Cavendish Professor in the University of Cambridge, he was destined almost from birth for a scientific career. But to succeed such a distinguished father has its disadvantages as well as its advantages. Comparisons are inevitable, and the work of the fourth Lord Rayleigh was apt to be under-estimated by those who could not but remember the immense contributions to knowledge, both mathematical and experimental, which had already emanated from his family home at Terling.

Lord Rayleigh's scientific activity throughout his life was consecrated to experimental physics. The work of most interest to astronomers with which his name will always be associated was the determination of the age of rocks by comparing the relative quantity of the radioactive parent substances, uranium and thorium, and their decay products in various minerals.

Until these observations were made no possibility existed for any, even approximately, accurate determination of the units of geological time. The order of the various strata could, of course, be ascertained and some idea of the relative duration of the geological periods could be formed by comparing their relative thickness. But to obtain any real estimate of the time-scale was beset with difficulties. Rates of denudation depend upon climate and everybody knew how much the climate had changed even in the comparatively short period between the Glacial Epoch and the present day. Above all, the celebrated estimate of Lord Kelvin, based on the assumption—very reasonable in those days—that the maximum energy the Sun could evolve was the amount derived from gravitational contraction, clamped an upper limit of 20 million years on the time-scale, which was utterly incompatible with the requirements of the geologists.

The proof by Lord Rayleigh in 1905 that the uranium-helium or thorium-helium ratio was the same in minerals of the same geological period and that this ratio led to a time-scale which could be laid down with considerable accuracy, and went back as far as fifteen hundred million years, came as a great relief to all students of geology and palaeontology. The uranium-helium ratio gave minimum figures since part of the helium might have escaped; the uranium-lead ratio gave maximum figures, since part of the lead—for in those days the differences of atomic weight between the various isotopes were not suspected—gave maximum figures. At last a fairly accurate geological time-scale was in sight.

For astronomers the main interest lay in the fact that a definite proof had been given that the Earth had existed for well over a thousand million years in conditions at any rate not widely dissimilar to the present, and consequently that the Sun must have existed for at least an equal period. This, of course, put an end to the view that solar heat was due to gravitational condensation. From the next tentative suggestion, that the solar heat might derive from radioactive sources to the present view about the origin of stellar energy was, of course, a long road, but the first step had been taken towards a recognition of the importance of nuclear phenomena in cosmological processes.

Rayleigh's work on the luminosity of the night sky was also of interest to astronomers. His discovery and investigation of active nitrogen was of more importance to chemists. As was inevitable in the case of a man working largely in a private laboratory, he spent much of his time in later years dealing with problems which did not require the immense paraphernalia which modern

physics involves. But mention must be made of the very interesting work he did during the war on the experimental reproduction of pebbles of regular shape, a typical example of his ingenuity in tackling a problem which at first sight seemed immune to exact physical investigation.

Lord Rayleigh's accurate and conscientious work as an experimentalist will assure him of a lasting place amongst the scientists of this country. In private life he was a man of great charm once the protective crust caused by his shyness had been pierced. Anyone who enjoyed his hospitality at Terling Place, where he felt really at home and spoke freely and without restraint, will always remember his unfailing courtesy, his penetrating conversation, spiced with a sense of humour, and his unflagging interest in all that concerns physics and related branches of science.

He was elected a Fellow of the Society on 1920 January 9.

CHERWELL.

ARTHUR ROBERT WESLEY, son of W. H. Wesley, Assistant Secretary of the Society from 1875 to 1922, was born at Burlington House on 1880 December 27. He was well known to many Fellows, as he assisted his father in the office for some years until his father's death in 1922 when he joined the firm of Wheldon and Wesley. His father was not permitted to be elected a Fellow while serving as Assistant Secretary, but he himself was a Fellow from 1923 May 11 until his death on 1946 December 23.

PROCEEDINGS OF OBSERVATORIES

Royal Observatory, Greenwich

(Director, Sir Harold Spencer Jones, F.R.S., Astronomer Royal)

Arrangements for the move from Greenwich to Herstmonceux have proceeded, and it is hoped that the "First Stage" may take place during the summer of 1948. This will include the Nautical Almanac Office, the Chronometer Section, the Magnetic and Meteorological Department, and the Secretariat; the Astronomer Royal will transfer his residence to the Castle, and Flamsteed House will terminate a service which it has performed for over 270 years.

Plans for the Solar Building are complete, and work on it has commenced; it is hoped to have it ready by the end of the year. The dome is part of the gift of Mr A. M. Newbegin, and his telescope will be erected in it both as a mount for the photoheliograph and as a visual equatorial in its own right; it is planned to undertake observations of occultations, and also to use it for general instructional work with the junior members of the staff.

The building will house two spectrohelioscopes (one being from the Newbegin Observatory) and a three-prism spectrograph of 6 feet focus, which can also be used with an extra half prism in the Littrow arrangement, giving an effective seven prisms. This instrument, which is suitable for eclipse work when required, was received shortly before the war. There will also be an office and measuring-room, a darkroom and a small workshop for minor jobs. As soon as the building is complete the Solar Department will move. Provision is being made, in addition, for an adjoining cellar, to contain larger apparatus which requires constancy of temperature; it is hoped to complete this about the same time.

The temporary huts to the south of the Castle have been converted, in the present housing shortage, into a hostel.

The 26-inch and 28-inch refractors have both been dismantled, as they were deteriorating in their damaged domes. The 28-inch is in store at Herstmonceux, and a synchronous motor-drive is being prepared for it; most of the 26-inch has been sent to Newcastle for the incorporation of roller bearings, which will involve fairly extensive structural modifications. The 30-inch reflector will not be remounted on the 26-inch refractor mounting but will be replaced by a counterpoise.

A Second Reversible Transit Circle, which was installed at Melbourne and has been presented to the Royal Observatory by the Victoria Government, will be erected at Herstmonceux as soon as possible. It has an 8-inch objective of 12 feet focal length and an impersonal micrometer, to which it is planned to fit a motor-drive.

Meridian Department.—The restricted programme of observations with the Airy Transit Circle has continued. 104 observations of the Sun, 76 of the Moon, 11 of Venus and 8 of other planets were obtained, together with 1050 transit and 779 zenith distance observations of standard stars. The preparation of the First Greenwich Catalogue of Stars for 1950 is nearing completion.

A list of stars to be observed for time and latitude has been prepared for the Photographic Zenith Tube at the latitude of Herstmonceux. The selection, according to photographic magnitude, was made with the aid of the Franklin Adams charts. These stars will be observed with the Reversible Transit Circle to tie them to FK3. They will also be observed at Washington, by the kind cooperation of the Director. A great deal of further study of the Reversible Transit Circle has been carried out. The pivot errors have been determined in various ways; they are certainly small, but it has proved difficult to disentangle a possible elliptical coefficient from flexure in the measuring apparatus. The apparent errors also depended on the direction of rotation of the instrument; as a result, it was decided to substitute plain bronze end-bearings for the self-aligning ball-races originally supplied, since this made it possible to reduce the end-pressure from 32 lb. to 8 lb. Investigations are in progress on the microscope screw errors; an apparent periodic error was found to be of subjective origin, caused by the comb which indicates the rough reading, and improved indicators are being substituted.

Time Department.—The full installation at Abinger of twelve quartz-crystal clocks operating on floating batteries was completed by the Post Office engineers in February. The beat-counters originally fitted proved unsatisfactory, and reliable information on performance was therefore largely restricted to those standards which directly controlled dividers and phonic motors. New rotary beat-counters were fitted in November and are operating efficiently. Various electrical faults have occurred, particularly in the dividers and thermostat circuits. The full potentialities of the clocks have not therefore been realized, but useful experience and information have been obtained, and considerably improved conditions may be expected during 1948.

At Greenwich six similar clocks were installed in October. As no suitable cellar accommodation was available the crystal oscillators have been installed in small partitioned enclosures in a ground-floor room, but adequate ambient temperature control has proved difficult. Tests are now in progress and the clocks will be brought into full use as soon as possible.

Five new standards employing ring-type crystals have been brought into use at the Post Office Radio Branch Laboratories at Dollis Hill, and results have been communicated daily since November. For the operation of the Time Service, therefore, information is now available on twelve clocks at Abinger, six at Greenwich, eight at Dollis Hill and one at the National Physical Laboratory. New computing methods have been introduced to ensure the most efficient use of the information available. During the latter months of 1947 the best performances were shown by the Abinger standards C3 and D3, which were therefore employed as prediction clocks.

The increasing uniformity of rate has made it necessary to take account of polar motion in assessing clock performance. The change of longitude implicit in the polar motion can be fairly well estimated for Greenwich from the Washington latitude results alone; these have been communicated with great promptness, by the kind cooperation of the Director of the Naval Observatory, and it is found that correction for the effects of polar motion results in a straighter run of apparent clock errors, and so in more reliable prediction. Greenwich Time is still the time based on the actual meridian, not the mean one, and the effect of polar motion is reintroduced in computing it; but the monthly bulletin of "Times

of Reception" also gives, from 1947 January, corrections to eliminate the polar motion (so far as the Washington data alone permit), since this time is more suitable for comparison with crystals.

Two hundred and nineteen time determinations have been secured at Greenwich during the year, by two observers only. The probable error is appreciably less than at Abinger, partly on account of the very intensive practice which is evidently involved and partly (it is believed) through climatic factors.

A number of new observers have been trained on the small transit at Abinger, and the number of observations used for the determination of clock error was 94. The alterations and modifications to the Bamberg transit instrument, referred to last year, have been completed, and the instrument installed at Abinger in July. 88 observations have been obtained, and a preliminary survey of the results indicates that the probable error is about two-thirds that of the Abinger small transit instruments. The scatter of the levels is noticeably reduced.

The normal programme of reception and measurement of radio time signals has been continued. Signals controlled by the Royal Observatory have normally been sent from Abinger, but Greenwich is equipped as a reserve for B.B.C. and hourly time signals. A short series of experimental tests has been carried out on the accuracy of short-wave time-signal reception. The results are being examined and further tests may be planned. Preliminary reception tests have also been made at Herstmonceux and will be continued when modifications have been completed at the radar station at Pevensey.

Work on the new control room at Abinger is approaching completion, and some of the equipment for a similar installation at Greenwich has been constructed. An improved model of long-wave time-signal receiver, designed and constructed in the Electronics Laboratory, is now undergoing test. An accurate frequency comparator of Post Office design has been constructed and installed, and is now in regular use. The low-power transmitter, used for the daily constant-frequency emission, was replaced by one of greater power in April, and new ancillary equipment designed and installed. Negotiations are in hand for the erection of a quarter-wave vertical aerial on another site to replace the inverted L aerial now in use. These transmissions are now very greatly appreciated by many Government establishments and commercial firms but, owing to the limited power available, useful reception is only possible over a moderate area. Consideration is being given, in collaboration with other departments, to the establishment in this country of a comprehensive service of standard frequency and time signals, similar in range to the service of WWV. The Observatory will cooperate to the full if this scheme is adopted.

Mr Smith and Mr Pope visited Paris in November and examined the work and equipment of the Bureau de l'Heure and Laboratoire National de Radio-électricitè. It is hoped that cooperation may be facilitated by the visit.

Observatory Laboratory.—The main emphasis has been on the Photographic Zenith Tube. The instrument now differs very radically from the original Washington one in almost all respects, and the modifications and innovations are entirely based on extensive experimental and planning work in the Laboratory. The optical method of levelling the photographic plate, devised a year ago, has now been tested and found adequate. A description has been published in the *Journal of Scientific Instruments.* The original optical method for assuring constant scale value has been modified by the introduction of a second mirror

at the lower end of a long silica rod; a null indication is thus obtained, independent of temperature variation.

Experiments on the mercury artificial horizon have continued; for studying stability of the level a capacity bridge has been constructed which proved capable of detecting displacements of the order of 10^{-8} inch, corresponding to angular displacements considerably less than 0·01 second of arc, the accuracy aimed at.

Consideration has been given to the design of a simple mechanism for making corresponding time-marks adjacent on the plate. A modified driving system for the carriage has been constructed by Messrs Grubb, Parsons and is now ready for test. The special plate-measuring machine has been subjected to further tests.

Apart from the Photographic Zenith Tube, experiments have been in progress to test the possibility of using a reversible pendulum as a standard of level. Two types of suspension are being tried, and two methods of reversal. Work on the motor drive for the Bamberg transit has been completed. An investigation of star trails on Cookson plates, to study atmospheric perturbations, has been completed. Tests were carried out on the Furt microphotometer in the experimental form developed by Messrs Ferranti; the metrological aspect was the main object of the study. Preliminary experiments were carried out on the silica optical squares required for the Horizontal Transit Instrument.

Solar Department.—The Sun was photographed on 254 days in 1947. Up to November 30, there is one day (March 27) unrepresented in the combined Cape-Greenwich series. Cape original and duplicate negatives have been received up to 1946 December 31. Available Kodaikanal plates required to fill the gaps in the combined series have been received up to 1946 October 20. A print of a Mount Wilson photoheliogram for 1941 May 31 and a positive on glass for July 29 have been kindly presented by the Director of the Mount Wilson Observatory.

The measurement of 210 plates has brought the measures of the combined series up to 1945 January 16.

The provisional mean daily sunspot number (Wolf number) from Greenwich counts alone is 152 for 1947 as compared with 93 for 1946. Tables of the mean daily areas and mean latitudes of sunspots for each solar synodic rotation in 1939, with general notes thereon, are being published in *Monthly Notices*.

The Sun's disk was observed in $H\alpha$ with the spectrohelioscope on 148 days; on 31 of these, observation was possible only for 15 minutes or less. 219 measures for any small line-of-sight motion were made on normal and flare patches of bright flocculi, most of these measures also giving the effective line-width of $H\alpha$; 303 measures were also made on dark filaments on the disk and 25 measures on limb prominences. Line-of-sight velocities for dark filaments exceeded 100 km./sec. in six cases, the highest value being 155 km./sec. outwards from the Sun on June 24. 141 sets of photometer measures were made collectively on normal bright flocculi and flares. In two cases the maximum central intensity of $H\alpha$ exceeded that of the continuous spectrum 15 A. from the line.

In all, 63 solar flares were recorded. As shown by the joint occurrence of a sudden radio fade-out and a pronounced geomagnetic crochet on the Abinger magnetograms, intense but probably short-lived flares occurred (when direct solar observations were impossible) on April 6 at $11^h\,52^m$ U.T. and August 1 at $15^h\,17^m$. Both flares were of special interest in connection with reported

observations of "solar noise". A paper on geomagnetic crochets recorded at Abinger 1936–46, completed during the year, is being published in *Geophysical Supplement*.

Astrometry and Astrophysics.—All 90 plates of the declination zone −56° to −60° have now been received from H.M. Astronomer at the Cape. In order to improve the distribution of catalogue stars in parts of the zone away from the Milky Way, the region between 22^h and 4^h of right ascension has been re-photographed with the wide-angle lens at the Cape with an exposure of 16^m instead of the normal 8^m. The resulting gain of about $0^m{\cdot}6$ enables the 118 stars per plate on the short-exposure plates to be brought up to 148, the comparable density for the region where the galactic equator crosses the zone being 200. All 23 long-exposure plates have now reached Greenwich.

Standard coordinates for a total of 5600 stars have been computed and checked for 70 of the 90 plates in the zone, and 41 have been measured and completely reduced to the stage of obtaining the residuals "measured *minus* computed". In addition, 11 of the long-exposure plates have been measured and reduced, the results for stars common to the two series showing a gratifying accordance with those from the short-exposure plates.

Comparison of spectra secured with the Yapp reflector, since aluminizing the main mirror and blooming the optical components of the spectrograph, with spectra of the same stars obtained before the war with silvered surfaces and unbloomed lenses and prisms confirms the expected gain in the ultra-violet region, which is that for which the slit spectrograph was designed. For the same exposure time a considerable extension in the ultra-violet can be observed, or alternatively the same density as before at a given wave-length can be obtained with an appreciably shorter exposure. Deposits of industrial grime on the surface of the 36-inch mirror have already appreciably reduced its reflecting power, however, and a light wash with alcohol, though it effected a temporary improvement, has not been repeated, since it enlarged existing pin-holes in the aluminium surface to an extent which causes some concern.

The programme of observing the ultra-violet region of the spectra of late-type one-spectrum spectroscopic binaries in the hope of detecting hot companions has been continued, using the 3-prism train, one lens of the one-prism system having suffered damage in the blooming process. The damage has now been repaired, and the work will be returned to the faster instrument in due course. In all, 58 spectra of 37 stars have been secured. Plates of the spectrum variable γ Cass were also obtained on 5 nights during the year.

The vacuum distillation plant for coating optical surfaces with metallic or with anti-reflection films has been erected during the year, and experience is now being gained in the coating of mirrors with chromium, aluminium and other metals. The films obtained up to the present appear up to good commercial standards (though their durability has yet to be proved), but it is hoped to improve the technique further, in particular by eliminating pin-holes in the deposit.

Nautical Almanac Office.—Throughout the year, there has been a gradual overtaking of the arrears in printing, and it is hoped that, beginning with the publications for 1950, it will prove possible to advance the dates of publication.

Very little progress has been possible with the outstanding astronomical investigations; the discussion of the 1943 occultations is in course of publication in the *Astronomical Journal* and it has been decided to publish the complete lists of reduced observations in the Greenwich publications.

The whole of the computations for the volume of *Apparent Places of Fundamental Stars* have continued to be supplied by the Offices to which the calculations were originally allocated. The Office of the *Connaissance des Temps* has been working under difficulties and finds it impossible to prepare its calculations up to schedule. It has therefore been agreed that, for the volume for 1950, the Nautical Almanac Office will be responsible for the computations for the first 216 stars of the normal Paris allocation.

Proposals have been drawn up for the complete revision of the *Abridged Nautical Almanac*, the main change being in the tabulation of Greenwich Hour Angle instead of Right Ascension, with consequent rearrangement.

In addition to the usual publications of the Office, the reprinted editions of *Planetary Coordinates for the years* 1940–1960 and of *Five-figure Natural Trigonometrical Tables* have been published during the year. Accounts have been prepared for publication of methods of applying the National machine to the solution of differential equations and to the calculation of apparent places of stars. The distribution of war-time issues of the *Nautical Almanac* to those on the exchange list has now been completed, as far as postal facilities permit.

The Office continues to be responsible for the computational work necessary for the latticing of charts required for the Decca system of navigation. A comprehensive report on the methods of computation used has been prepared.

In May, Mr D. H. Sadler, the Superintendent, visited astronomical and computational organizations in U.S.A.; in the course of a prolonged visit to the U.S. Naval Observatory, he had the opportunity of seeing the work of the American Nautical Almanac Office and of discussing matters of mutual interest to the two offices with its Director, Dr G. M. Clemence.

Miscellaneous.—The Astronomer Royal formed one of the Royal Society delegation to the Indian Science Congress held in New Delhi in January and afterwards visited observatories in India for the purpose of advising upon future astronomical developments in India. In February he visited Australia, at the invitation of the Commonwealth Government, to advise upon astronomical developments in Australia. One outcome of this visit has been the decision by the Commonwealth Government to provide a 74-inch reflecting telescope for the Commonwealth Observatory, Mount Stromlo.

The Chief Assistant, Dr R. d'E. Atkinson, paid an extensive visit to the new Solar Observatory at the Kanzelhöhe in Carinthia, during the summer, after first visiting a number of German observatories. As a result of his representations, the Occupation Troops agreed to build an additional tower for the coronagraph, higher up the mountain, and this has since been completed and handed over. The Austrian authorities made some staff changes, and help was given with adjusting and setting up instruments. Cooperation between the Observatory and Greenwich will continue. Arrangements were made for a daily exchange of coronal data with the Wendelstein Observatory, Bavaria, by teletype.

Royal Observatory, Edinburgh

(*Director, Professor W. M. H. Greaves, F.R.S., Astronomer Royal for Scotland*)

Spectrophotometry.—The study of line intensities in early type stars of magnitude 5·0 or brighter has been continued, using the 36-inch reflector and the two-prism arrangement of the Hilger Spectrograph. During the year 1947,

106 spectra were secured on 42 nights. The comparison spectrum consists of the more prominent neon, helium and mercury lines given by an "Osglim" neon lamp with a suitable blue filter. This is kept in operation throughout the exposure of the stellar spectrum. Errors from scattered light are negligible. The plates are calibrated by a multiple slit spectrograph of comparable dispersion, the light source of which is intermittent so as to resemble the effect of trailing the stellar spectra.

The spectra are measured with a Moll type microphotometer constructed in the Observatory for use as a non-recording instrument. The measurements are made at a number (upwards of one thousand) of corresponding points, so that for different plates the measures are made at the same wave-lengths. The results are expressed as percentages of continuous background, and not only all the plates of a single star but all the plates of any chosen group of stars can be combined without loss of any features common to the group. Such a combination of plates naturally reduces the obscuring effect of the graininess of the emulsion. In this way the effect on the assumed background of faint lines can be examined, such lines being shown up in the group means, although on individual plates they are hidden by plate grain. Special attention is being paid to the first three members of the Balmer series (so as to detect incipient emission) and to the (interstellar) D lines.

Further experiments have been made on the effect of weak subsidiary lighting of the emulsion during the exposure. The single and two-prism arrangements of the stellar spectrograph and the calibration spectrograph have been fitted to allow of this, adequate uniformity being secured by a diffuse beam of light which reaches the emulsion after reflection from the final prism face. But, so far, subsidiary lighting has not been used for the plates of the current programme. It would become advantageous if the programme were extended to include fainter stars.

Ten-inch Wide-Angle Camera.—Good progress is being made with the construction, by Messrs Kipp and Zonen of Delft, Holland, of the star actinometer which will be used for the measurement of the photometric plates. Delivery is expected during the first half of 1948. Pending its installation the work with the 10-inch camera had been confined to test-plates in preparation for the photometric programme. It is proposed to employ the coarse diffraction wire grating whose construction has been reported previously, but the grating method as normally used is open to criticism on the grounds that the diffracted images are elongated and are not strictly comparable with the direct image. To meet this criticism the flint component of the camera objective has been displaced relatively to the crown components so as to disperse the direct image. The direct image and the first diffracted image on one side are now equally elongated, and these images will be used for the establishment of a photometric scale. The first diffracted image on the other side is considerably more elongated, and it is proposed to include measures of this image in the programme with a view to checking the amount of the error introduced by image elongation in the grating method as normally used.

Solar Work.—A combined spectrohelioscope and spectrograph has been constructed at the Observatory and has been brought into use. The instrument has been designed by Dr Ellison and it is similar to the one which was developed by him for his investigation, at Sherborne, of the spectra of chromospheric flares.

The instrument is mounted in the Optical Room, the primary image being formed by a 5½-inch achromatic lens of 18 ft. 3 ins. focal length. The lens is fed by the Eichens Siderostat mounted on the Observatory roof. The dispersion element comprises a Rowland plane grating (ruled area 5½ in. × 4 in.) which is illuminated by means of a 4-inch Grubb achromatic lens of 16 ft. focus, working on the autocollimating principle. Special attention has been paid to the problem of reducing scattered light. The casing of the instrument has been lined throughout with black velvet and stops have been suitably located so as to blot out the various unwanted images of the primary slit formed by reflection from the lens surfaces. The monochromatic image in $H\alpha$ light is formed by the synchronous oscillation of the scanning and viewing slits, following the plan evolved by F. J. Sellers.

An important feature of the instrument is the mechanism for the rapid change-over to photography of the spectrum. This provides for recording the spectrum of any short-lived chromospheric phenomenon seen in the spectrohelioscope, which for this purpose serves primarily as a "scouting" device. Any region of the 1st, 2nd or 3rd order spectrum may be projected on to a 10 in. × 2 in. plate-holder and the spectrum photographed within 30 seconds of the first appearance of the phenomenon.

It is intended to use the instrument for the observation of flares at certain fixed hours, in accordance with the I.A.U. programme, and for the investigation of line intensities in the spectra of flares and metallic prominences. For the calibration of plates a high-speed rotating sector can be introduced into the beam immediately in front of the primary slit.

Workshop.—A modern milling machine, lathe and vertical drill have been added. In addition to solar equipment the work carried out during the year includes the construction (mainly by Mr A. B. Partridge) of a calibration spectrograph. This instrument has been designed and made in preparation for ultraviolet spectrophotometry and its dispersive element consists of a single quartz prism.

Staff.—The authorized staff of the Observatory now consists of the Astronomer Royal for Scotland, two Principal Scientific Officers, two Scientific Officers, one Senior Assistant (Scientific) and one Assistant (Scientific), a clerk-typist and a porter-messenger. Dr M. A. Ellison joined the staff as Principal Scientific Officer on 1947 October 1. The responsibility for the main programmes of the Observatory is divided between the two Principal Scientific Officers, Dr Baker being in charge of the spectrophotometric work and Dr Ellison in charge of the solar work and of the photometric programme with the 10-inch wide angle camera. There are at present three vacancies on the scientific staff, viz. for two scientific officers and one assistant (scientific).

Royal Observatory, Cape of Good Hope

(*Director, Dr J. Jackson, F.R.S., H.M. Astronomer*)

Reversible Transit Circle.—The observation of standard stars in the zones −64° to −80°, begun in 1946, was continued. A reversing prism is used and, when necessary, screens to cut down the stars to about the eighth magnitude. During the year 6546 transits and 6308 declinations were observed. The

following observations of bodies in the solar system were made:—

Sun	180	Jupiter	15	Ceres	10
Moon	34	Saturn	12	Pallas	5
Mercury	73	Uranus	10	Iris	13
Venus	114	Neptune	15		

The reductions are well up to date, including the comparison of the planetary observations with the calculated positions.

The observations of 5373 stars south of declination $+35°$ observed in the years 1936–1944 have been ledgered and the means compared with the Albany General Catalogue. The differences have been analysed in 5° zones and hourly groups and a copy of the results sent to Washington.

A complete copy of the observations of standard stars for the zones $-56°$ to $-64°$ has been sent to Greenwich.

Photographic Zone Observations.—The plates required to complete the zones $-56°$ to $-64°$ were secured early in the year and of the 220 plates required for the zones $-64°$ to $-80°$, 173 were secured between May and December. It is hoped to complete the photography in 1948. All the plates for the zone $-56°$ to $-60°$ have been sent to Greenwich where they are being measured.

During the year the principal effort was devoted to finishing off the zone $-35°$ to $-40°$, an area of the sky which has been very poorly observed in the past. Of the 12,000 stars measured in this zone only about 8300 had been previously observed in precision catalogues, although about 1300 others had been observed in the Cordoba zones. For these 9600 stars proper motions have been determined and for over a quarter of them second or third determinations have been made either because the first determination was based on poor material or because the star appeared important. For the other 20 per cent of the stars only C.P.D. places were available and these are not sufficiently accurate for proper motion determinations.

The plates of the zone $-52°$ to $-56°$ have all been measured and we are now analysing the residuals for positional corrections, colour and magnitude corrections.

For the zone $-60°$ to $-64°$, 6724 stars have been selected for measurement and the standard coordinates have been completed for about a third of them.

For zones $-64°$ to $-80°$ the accuracy of the setting of the telescope is being checked as soon as possible after the plates are developed. It is possible to have the plate centres accurate to a few seconds of arc and the hour angle at the middle of the exposure less than one minute of time.

Dr G. G. Cillié continues to classify the spectra of stars in the zone $-35°$ to $-40°$ not contained in the Henry Draper Catalogue.

Victoria Telescope.—The telescope has been principally used for taking plates in the parallax programme. During the year 2972 plates were taken on 246 nights, and 2106 plates were measured. About 9900 remain in hand to be measured.

The total number of stars for which the parallax has been determined since this programme was started in 1926 is 1533. A list of 100 new determinations has been sent to the Society.

The observing programme now consists of about 360 stars, of which a third are important stars being re-observed, another third faint stars of large proper motion largely from Luyten's lists, and the final third a miscellaneous collection of stars.

During the year a start was made in determining the visual and photographic magnitudes of the parallax stars by comparison with stars in the Harvard standard E regions at declination $-45°$. Plate holders were constructed for both the 24-inch photographic and 18-inch visual telescopes so that areas of only 1 sq. cm. would be exposed at a time, and the telescope was pointed so that either a parallax star or a standard star fell near the centre of the area. Two or three exposures were generally made of each star. This arrangement was in use for about 40 nights, beginning at the end of April, but on the whole the weather was very poor for photometric work. About 700 observations were made.

In the course of this work it was found that changing definition introduced unexpectedly large errors. It was not uncommon for consecutive exposures of one minute on a star to show changes of over 0·1 magnitude, as measured in the Schilt photometer, when to the naked eye the sky was brilliant. This is due to the images being of different sizes and the light having a different number of silver grains to work on. It appears that the Fabry method is not subject to such large errors from this source and arrangements are being made to carry out as much as possible of the work by the Fabry method. At present it is possible to get photographic magnitudes by the Fabry method with the 24-inch lens in about the same exposure time as visual focal images with the 18-inch lens for stars of spectral types G–K, say in 1 minute for stars of magnitude 8·5 visual and 9·5 photographic. It is hoped that a faster Fabry arrangement can be made.

Photographic and Photovisual Magnitudes.—Early in the year Dr Redman, who had been securing plates for us with the photometric cameras mounted on the unfinished 74-inch reflector at Pretoria, was appointed Professor of Astrophysics at Cambridge. Before he left, however, he managed to secure the 96 pairs of plates required to complete the work to declination $-64°$. He has thus taken all the plates for the zones $-35°$ to $-40°$ and $-52°$ to $-64°$. He also obtained 17 pairs of plates, comparing some of the Harvard E regions at $-45°$ with Kapteyn Selected Areas at $+15°$. The cameras have now been sent to England, where, after the lenses have been coated with anti-reflection films, Dr Redman has offered to try and secure the plates connecting stars in the Kapteyn Areas at $+15°$ with stars of the north polar sequence. When this is done it will be possible for us to determine magnitudes on the system of the north polar sequence with an accuracy not previously obtainable because of uncertainty in the magnitudes of stars observable from South Africa.

During 1947 the reduction of the photometer measures to photographic and photovisual magnitudes on the scale previously adopted for the E regions has been completed for the 12,000 stars in the $-35°$ to $-40°$ zone. The magnitudes, with few exceptions, depend on measures from two plates with exposure times of 15 minutes or 3 minutes.

Series of stars on these plates were also measured to strengthen the scale and zero point for the zone $-30°$ to $-35°$, the plates for which had been taken earlier at the Cape. The revision of the photographic magnitudes for the 13,000 stars of this zone is complete, but a troublesome systematic error in the photovisual magnitudes is still being investigated.

Once again a considerable amount of time has been devoted to the attempt to set up accurate standard magnitudes for the nine E regions. During the year the measurement of the new series of plates comparing the E regions with each other, with the Pleiades and with the Southern Comparison Stars for Eros has been completed and the preliminary reductions made. The measurements

of the photovisual magnitudes of the Eros stars have been analysed for the determination of corrections depending on the position on the plate in the hope of finding the clue to the discrepancies previously noted in the zone work. The corrections actually found were satisfactorily small. The project of extending the E region sequences by measuring all the bright stars in areas $6° \times 6°$ surrounding each E region and by measuring selected stars down to $14^{m}{\cdot}0$ on plates taken with the Victoria Telescope has been continued. The measurement of focal images of bright stars on ordinary plates by using larger diaphragms than normal in the Schilt photometer was not entirely satisfactory and it was decided to carry out this part of the programme with the Fabry photometer attached to the Astrographic Refractor.

All suitable opportunities have been taken to use the Fabry photometer to make observations for determining an absolute scale of magnitudes for selected stars in the E regions and to continue the observation of stars brighter than magnitude 5·0 south of declination $+6°$. In all 3182 observations were made on 90 nights—generally two images of one minute each. Rotating sectors were used to cut down the brighter stars. The observations in the E regions extend to magnitude 8·3 photographic and 7·5 visual. About 80 per cent of the observations required for the photographic magnitudes have already been secured and about 50 per cent for the visual. It is hoped to extend the programme for the E regions to fainter stars with the Victoria Telescope. Routine observations are now made each night for determining the general sky illumination by an arrangement which magnifies the effect on the Fabry images by nearly one hundredfold—this enables the small correction required for sky illumination to be accurately applied.

Photoheliograph.—The Sun was photographed on 345 days, 711 plates in all being taken. 24 of these plates have double exposures for the determination of the zero of position angle. Visual observations of this quantity have been made weekly.

Occultations.—Seventy-one observations of 34 phenomena were observed with various telescopes of the observatory, 23 being by Mr Davies, a local amateur astronomer.

Variable Stars.—During the year Mr de Kock made 5093 observations of 146 variable stars. These have been forwarded to Harvard for incorporation with the observations of the American Association of Variable Star Observers.

Comet 1947*n*.—This comet, although seen from Cape Town by many people on December 8, could not be observed from the observatory because of the mountains, or clouds on them, for more than a week. It was photographed for position on December 16, 17, 20.

Publication of Results.—It has so far been impossible to publish any of our results since 1938. A special typewriter and a vari-typer have now been received and it is hoped that it will soon be possible to start typing results ready for reproduction by photolithography.

Cambridge Observatories
(*Director, Professor R. O. Redman*)

Staff.—Professor F. J. M. Stratton retired at the end of the academic year, on reaching the age limit, and Professor R. O. Redman was appointed to succeed

him as Director from October 1. Dr A. Beer was appointed Observer at the same date. Dr H. Brück, Assistant Director, resigned on September 30, to become Director of the Astronomical Department of the School for Cosmic Physics, Dublin, (Dunsink Observatory), and Mr H. E. Butler, Observer, resigned on November 30, also to go to Dublin. Mr A. B. Reeder, Assistant, resigned at the end of the year to join the staff of the Cavendish Laboratory. None of these posts had been filled at the end of the year. In addition, Mr E. T. Pierce, Observer, and Mr T. Arthur, Assistant, have been on prolonged sick leave. In common with most other similar institutions the Cambridge Observatories are finding it very difficult to recruit suitable men to keep their staff up to strength.

Apart from members of the staff the following have worked at the Observatory during a part, or the whole of the year: Dr W. H. Steavenson, M. K. M. Aly, R. L. Baglow, M. Ballester, P. B. Fellgett, G. J. Odgers, G. Righini, J. H. Shaw, H. V. Stopes-Roe.

Buildings.—The Newall Dome has been repainted. Temporary repairs have been necessary to three other domes, to make them reasonably weather-tight until such time as they can be entirely re-covered.

Stellar Work.—Two hundred and seventy-three spectrograms have been obtained with the Newall telescope on 117 nights. The greater part of the observing time has been devoted to completing a photometric programme in the near infra-red of the *Ca* II triplet and some members of the hydrogen Paschen series. Spectra have also been photographed in the ordinary photographic or visual region; of ρ Cass, o Ceti, VV Cephei, UU Aurigae, a few visual double stars and also the white dwarf o^2 Eridani B.

The 3-foot reflector has been used mainly for photometry of extragalactic nebulae in three colours. An attempt was also made with a slitless spectrograph and a polarizing analyser to photograph Wolf 1346, to test suggestions by Blackett as to the magnetic field of white dwarfs. No Paschen-Back effect could be detected, the results, however, being subject to rather large observational uncertainty. Preliminary tests have been made for measuring stellar radiation with a lead sulphide cell, also on the 3-foot reflector, the results being sufficiently encouraging for a start to be made in constructing more elaborate apparatus for infra-red photometry with lead sulphide or selenide cells.

Attempts are being made to measure the light curve of Algol accurately in infra-red and ultra-violet simultaneously, using the Fabry method, with apparatus mounted on the Thorrowgood refractor.

The Sheepshanks telescope has been overhauled for a new proper motion programme, to be based on Hinks' plates taken 40 years ago. The present telescope lens is not that used by Hinks and the effect of this change on the work needs to be investigated forthwith.

The Huggins reflector has been dismounted and the twin photometric cameras on loan from the Royal Observatory, Cape of Good Hope, are being temporarily installed in its place, for a programme intercomparing the Selected Areas at $+15°$ with the Pole. The ultimate object is to provide material for completion of the standardization of star magnitudes in the southern sky.

Dr Steavenson has continued his observations of novae in their later and fainter stages, and of the satellites of Uranus.

Fourteen lunar occultations have been observed during the year.

Solar Work.—The Director of the Kodaikanal Observatory has sent copies of K_{232} spectroheliograms up to 1947 September 30.

Observations were made with the spectrohelioscope on 141 days, mainly with a view to seeking phenomena which could be associated with bursts of radio noise, of which a continuous record is now being kept at the Cavendish Laboratory. Flares or very bright flocculi were observed on 41 days. In connection with the same radio work, polarities of sunspots have been observed with the McClean spectrograph whenever possible.

The infra-red spectrum of the Sun has been recorded in the region 2 to 12 μ with a thermocouple and a rock-salt spectrometer, chiefly to study absorption bands due to the Earth's atmosphere. To continue this research a small absorption tube with an effective path-length 10 feet has been built and is in use in the laboratory.

Long-delay wireless echoes.—An attempt has been made to detect long-delayed wireless echoes on a frequency of 13·455 Mc./s., similar to those reported by Störmer and van der Pol in 1928. Special transmissions from Ongar have been received with the present apparatus for 1-hour periods four times weekly during the last seven months of the year. Measurements of receiver sensitivity, considered in relation to the transmitter power and to the type of reflecting layer anticipated, have indicated that it should be possible to detect echoes having a delay of about 15 seconds. The results so far have been negative.

Atmospheric electricity.—Improved apparatus based on two cathode-ray recording systems is now in use to record field changes due to lightning flashes: in the one case for slow changes, with 6 seconds as the smallest time-constant in the circuit; in the other for fine detail, where the acceptance band of the amplifier is from 0·02 to 30 Kc./sec.

University Observatory, Glasgow

(*Director, Professor W. M. Smart*)

The work on the Systematic Motions of the Stars of the General Catalogue was continued by Dr T. R. Tannahill during the past year.

Mr P. A. Sweet, who joined the staff in 1947 October, has been engaged in two investigations: (i) On the origin of the magnetic field of sunspots; and (ii) On the effect of the ionization energy of hydrogen on high-frequency radiation at the base of the chromosphere. In the first, the interaction of ionized material with radiation in a vortex is shown to produce a magnetic field of the right order of magnitude.

Imperial College Observatory, South Kensington, London

(*Director, Assistant-Professor R. W. B. Pearse*)

This year, courses of instruction in astrophysics and spectroscopy have been given as usual.

Work on molecular spectra has been continued. Dr S. P. Sinha completed an investigation of the higher excitation energy states of the alkali-metal molecules shown by their emission, absorption and fluorescence spectra. Mr F. H. Bowen

devised a source for the study of long-series and recombination spectra of the alkali metals.

At an international conference in London on the emission spectra of the night sky and aurorae, the Director read a paper on the problem of the identification of the radiations emitted by the night sky.

University of London Observatory, Mill Hill, and University College Observatory

(*Director, Mr C. C. L. Gregory, Wilson Observer*)

The Radcliffe Telescope.—This instrument was used on 166 nights, during which observations made before and after midnight were 104 and 92 respectively. The total number of plates taken was 697, of which 654 were for parallax, 24 for proper motion, 3 on comets and 16 for experimental purposes.

A small modification was made in the Grubb control for the driving mechanism in order to extend its range to cover a considerable drop in the frequency of the electric mains supply during peak load; this has proved satisfactory.

A Hartmann diaphragm, originally constructed for testing the Wilson reflector, was adapted for testing the effects of maladjustment of the components of the 24-inch photographic lens in connection with an investigation of "magnitude equation", which was undertaken, at the suggestion of the Director, by Mr R. W. Pring.

Other instruments.—The Wilson telescope and 4-prism spectrograph were used mainly on γ Cassiopeiae. Both mirrors were aluminized by Messrs Grubb, Parsons Ltd.

The 8-inch Fry refractor by Cooke has been used mainly for instruction. Most of the 283 visitors to the Observatory during the year, which included parties from schools and colleges, made use of this instrument.

Some advance has been made towards the realization of the new mirror meridian instrument mentioned in the last annual report. Tests carried out by the Optical Works Ltd. (Ealing) on the adhesion of fused silica have, at last, been successful, and a prototype model is now in process of construction in the Observatory workshop.

Publications.—The first number of *University of London Typescript Circular* was completed in December. It contains an account by Dr Peachey of the variations which have been observed in the spectrum of γ Cassiopeiae, the first part being historical and the remainder dealing more fully with observations made by her during 1940 than appeared in the account in *M.N.*, **102**, 166, 1942. Copies are being sent to a number of astrophysicists to whom the technical details it contains might be of interest.

University Observatory, Oxford

(*Director, Professor H. H. Plaskett*)

Staff.—Miss E. F. Bellamy retired on July 31 after some 48 years service as Assistant at the Observatory. With her Uncle, the late F. A. Bellamy, she had been responsible for the reduction of the measures of the Vatican Observatory zone of the Astrographic Catalogue. From 1919 until the end of 1946, first

under the direction of the late Professor Turner and subsequently in collaboration with J. S. Hughes, Miss Bellamy played a vital part in the preparation and publication of the *International Seismological Summary*; in fact during the war she carried out the whole of the computation and publication single-handed. In addition her *Index Catalogues of Epicentres*, the last of which was published just before her retirement, have proved to be indispensable aids to the statistical study of earthquakes.

Dr M. G. Adam, Chief Assistant at the Observatory, was in October also appointed as University Demonstrator in Astronomy. Balliol College re-elected the Rev. P. J. Treanor, S.J., as Skynner Senior Student in Astronomy for a further year. Dr G. Merton, who has been working at the Observatory in a voluntary capacity since 1946 May, was appointed a Departmental Demonstrator in Astronomy on August 1.

Buildings.—The erection of a new, copper-clad, motor-driven dome over the solar telescope was completed by Grubb, Parsons in April. This has already proved to be a great assistance in the operation of the telescope.

Work.—In solar spectroscopy Dr Adam has completed the measurement of the interferometer-spectra obtained in 1946 for the determination of the solar limb-effect. Preliminary results from the nearly completed reduction give promise that the investigation may go some way towards clarifying this phenomenon. The solar telescope and spectroscope were in operation from April until the end of November. Foucault tests of the spectroscope revealed that the still imperfect definition was due to striae in the glass of the large prisms, and a marked improvement in definition was obtained by diaphragming off the worst of these striae. In this diaphragmed form the spectroscope was used during an exceptionally good observing season by Treanor to obtain the interferometer-spectra required to determine the profile of $Ca\lambda 4227$ by Shane's method. Experiments were carried out through the season on a new guiding device, and finally in October and November the Director succeeded in obtaining high-dispersion spectra of solar granulation. The measurement of these spectra will be commenced shortly.

A more rigorous method of computing the perturbations of cometary orbits is being tested by Dr Merton on the orbits of the periodic comets Gale and Tempel (2). Tests of emulsions suitable for cometary photography have been made by photographing the north polar sequence with a pair of $f/5{\cdot}6$ cameras of 20 inches focal length, mounted on the 12-inch Grubb equatorial. As a result an emulsion has been found which is not only fast but is also especially suitable for long exposures.

University Observatory, St. Andrews

(*Director, Dr E. Finlay-Freundlich*)

Staff.—Mr T. Ślebarski joined the Observatory as Research Student, with a U.N.E.S.C.O. Scholarship. Mr B. Bernheim, Jerusalem, entered as Research Student with a British Council Scholarship. Mr J. G. Bruce, Curator of the Mills Observatory, Dundee, joined the optical workshop as Assistant Optician.

Equipment.—During 1947 the equipping of the workshop was completed and the grinding of the mirrors for the 19-inch Schmidt-Cassegrain pilot model

was begun. The grinding and polishing machine, made in our own workshop, has now been in operation for several months. It will take mirrors up to 36 inches in diameter. The Corporation of Dundee has kindly offered to the Observatory the use of their 19-inch Newtonian telescope at the Mills Observatory on Balgay Hill.

Work.—Mr I. J. Campbell continued his analysis of the structure of globular star clusters and Mr Ślebarski his work on the internal structure of stars. Regular observations to determine the latitude of the Observatory were made with a newly purchased theodolite. With the Cook transit instrument preparatory observations were made for accurately measuring the longitude of the Observatory. These observations were carried out by Mr Campbell, Mr Ślebarski and Miss Rosa Rayner, the last an Honours student in Astronomy. At the 10-inch visual Refractor observations with a new photometer for the observatory in Warsaw are in progress.

Norman Lockyer Observatory, Sidmouth
(*Director, Mr D. L. Edwards*)

In addition to the exceptionally severe winter, from which Sidmouth suffered equally with the rest of England, weather during 1947 was again poor for night work and reduced the routine observational work well below the average. The general programmes, including colour temperatures, bright-line stars and various minor investigations have, however, been carried out as fully as possible.

Arrangements have been completed by which the Observatory (which since its foundation in 1912 has been maintained through funds provided by a few generous donors as a non-profit-making Corporation) will become "The Norman Lockyer Observatory of the University College of the South West of England, Exeter".

The Observatory will remain on its present site but the whole property will now be incorporated in the University College of the South West under a scheme adopted by the Councils of the College and of the Observatory Corporation. The observatory staff will thus become attached to the staff of the College and the Registrar of the College will become Secretary of the Observatory Corporation.

Under the revised Articles of Association the future Council of the Observatory Corporation will consist of not more than 20 persons nominated by the Council of the College and not more than five nominated by the Corporation. The Observatory will thus have an assured future, with greater possibilities of expansion.

Stonyhurst College Observatory
(*Director, Father J. P. Rowland, S.J.*)

As from 1947 December 31, this Observatory will be closed and no further reports will be issued.

Dunsink Observatory
(*Director, Professor H. A. Brück*)

Twelve years ago the last report on the proceedings of Dunsink Observatory appeared in this journal, written by the late Mr Charles Martin as Acting Director.

For most of the time after the late Professor Plummer's resignation of the Directorship in 1921, activities of the Observatory had been confined to providing a time service for Dublin and to serving instructional purposes.

In 1946 the property of the Observatory was acquired by the Government of Eire from Trinity College, Dublin, with a view to re-starting its activities as a centre of astronomical research. During the past year the Observatory was reopened under the auspices of the newly founded School of Cosmic Physics of the Dublin Institute for Advanced Studies. The academic staff consists at present of the Director, the Chief Assistant Mr H. E. Butler, formerly Senior Observer at the Solar Physics Observatory, Cambridge, and the part-time Assistant Mr F. J. O'Connor, who at the same time holds the position of Lecturer in Astronomy at Trinity College, Dublin.

Most of the present instrumental equipment of the Observatory is now obsolete. However, the 12-inch South Refractor has been overhauled and will be put into use again. The 15-inch Roberts Reflector has been dismantled also, and when overhauled is to serve for a proposed programme of photoelectric observations.

Observational work at Dunsink is to be devoted largely to solar research, and a vertical solar telescope is to be erected. A number of parts for such a telescope—amongst which are a 16-inch coelostat and a 15-inch concave mirror, have been lent to the Observatory by the Joint Permanent Eclipse Committee. A large concave grating spectrograph is to be attached to the solar telescope.

In the field of stellar astronomy observational material for the Observatory will be obtained in due course from plates taken with a 36-inch Schmidt-Baker telescope which is now under construction by the Perkin Elmer Corporation, Conn., U.S.A. The instrument will be the joint property of the Armagh, Dunsink and Harvard Observatories, and when ready will be mounted at the Harvard station in Bloemfontein, South Africa.

Dominion Observatory, Ottawa, Ontario
(*Dominion Astronomer, Dr C. S. Beals*)

Staff.—The appointments of C. S. Beals as Dominion Astronomer and of E. A. Hodgson as Assistant Dominion Astronomer were officially announced in May. Miss D. G. Askwith was appointed to the clerical staff in June and Mr L. P. Boucher was appointed librarian in August. During the summer twelve seasonal assistants were employed to help in the Astronomical and Geophysical programmes of the Observatory.

The Meridian Circle.—Observations were made on 70 nights, a total of 2316 transits and zenith distances being taken. The current computations have been kept up to date and back computations checked. A catalogue of over 20,000 observations on 2435 stars, observed during the years 1911 to 1923, has been compiled and is almost ready for publication.

The Time Service.—Observations of 2187 transits were made on 181 nights with the reversible, broken-type, Cooke transit. The four primary clocks were one Shortt, two Riefler, and one crystal clock. Time signals were transmitted daily to the railroads and were broadcast daily over the CBC chain of stations. Continuous broadcast of time signals on short wave over CHU was maintained with transmitters of increased power, making reception possible

in almost all parts of Canada. The synchronized clock systems in government buildings were also maintained throughout the year. Time signals were received daily from NSS and WWV and, commencing in December, a few from GBR. An electronic frequency converter for providing a sixty-cycle, crystal-controlled power supply was constructed by V. E. Hollinsworth and J. P. Henderson. The weight drive on the printing chronograph was replaced by a synchronous motor using this supply and operating with a gear ratio 365:366. A paper on the Canadian Time Service has been prepared for publication by M. M. Thomson.

Stellar Spectroscopy.—An extensive study of the P-Cygni type star HD 190073, based on high dispersion spectrograms from Victoria, was carried out by C. S. Beals and Miriam S. Burland. Wave-lengths have been computed for all lines measured and equivalent widths determined, using both microphotometer and intensitometer tracings. A paper entitled "The Photoelectric Temperatures of the P-Cygni Stars" has been prepared for publication by C. S. Beals and R. D. Hatcher. Temperatures for 52 stars were computed and these ranged from 10,000 deg. to 42,000 deg. Mr Hatcher was employed at the Observatory as a summer assistant in astrophysics. In continuation of the study by C. S. Beals of interstellar matter, 240 spectrograms from Victoria were measured for radial velocities of interstellar calcium and sodium by J. J. O'Connor.

Solar Physics.—Routine photographs of the solar surface were taken on 45 days and prints supplied to various government departments.

Meteoric Astronomy.—In cooperation with the Electrical Engineering and Radio Branch of the National Research Council of Canada, successful programmes of observation of the 1947 Perseid and Geminid meteor showers were carried out. These programmes combined radar, photographic and visual observations. Totals of 46 meteor photographs, 22,800 radar meteor echoes photographically recorded, and 1730 meteors visually observed were obtained in 57 hours of observations on eight nights. A preliminary account of the Perseid results has been prepared for publication by P. M. Millman, D. W. R. McKinley (NRC) and Miriam S. Burland. Progress was made in the plans for the establishment of two meteor observatories at Meanook and Newbrook, Alta., separated by a distance of 26 miles. Systematic meteor photography will be carried out at these stations in cooperation with a similar programme in the United States directed by the Harvard Observatory.

Theoretical Astrophysics.—The effect of radiation pressure in producing radial accelerations in the hydrogen atoms of a stellar envelope was investigated by J. A. Rottenberg, a summer assistant at the Observatory. A paper entitled "On the Acceleration of Hydrogen Atoms at the Surface of a High Temperature Star" was prepared.

Seismology.—During the calendar year of 1947 eight hundred and forty-nine (849) earthquakes were recorded at the stations of the Canadian network. Major shocks were reported to the Press and to Science Service, and registrations of local quakes were reported to Weston, Mass.

Teleseismic seismographs have been maintained in continuous operation at Victoria, Saskatoon, Ottawa, Seven Falls and Halifax; and in addition short-period instruments have been operated at Ottawa, Shawinigan Falls and Seven Falls. A seismic survey of the Precambrian Shield, making use of the rock-bursts at Lake Shore Mines, was commenced during the early summer

months. A control station was set up at Kirkland Lake and to date field stations have operated at Dane, Ville Marie and Temiskaming.

All Canadian registrations have been regularly reported through the medium of a monthly bulletin service. Monthly reports on the records obtained at the Quebec stations were supplied to the Shawinigan Water and Power Co. and the Quebec Power Co. The *Bibliography of Seismology* has been continued as a semi-annual publication.

Terrestrial Magnetism.—During the year magnetic observations were made at thirty-six stations, eight of these being exact re-occupations of Dominion Observatory stations and twenty-eight being new stations. Seven repeat and ten new stations were in the area between latitudes 42° N. and 48° N., and longitudes 69° W. and 83° W. One repeat and nine new stations were in the area between latitudes 62°·5 N. and 73°·7 N., and longitudes 92°·5 W. and 114°·5 W. Transportation in this area was effected by a Royal Canadian Air Force amphibious Canso aircraft. Nine new stations were established in the area between latitudes 72°·7 N. and 80° N., and longitudes 73°·9 W. and 100°·7 W. Transportation to these stations was by icebreaker. Observations made in the latter two areas restrict the north magnetic pole area to northern Prince of Wales Island.

An induction-type magnetometer, designed and constructed at the Observatory, performed satisfactorily, giving reliable indications of declination and other magnetic elements even in the environs of the magnetic pole. The usual spring and fall comparisons between field instruments and primary and secondary standards were made at Agincourt and Ottawa. The magnetic observatories at Agincourt, Ont., and Meanook, Alta., operated continuously during the year. A temporary magnetic observatory was established at Baker Lake, N.W.T., in December.

Gravity.—In southern Canada 1000 determinations of gravity were made with the Mott-Smith gravimeter. Besides a continuous set of observations along highways between Amherst, N.S., and Jasper, Alta., networks of gravity stations were established in south-eastern New Brunswick and in the mining areas of Ontario and Quebec in the vicinity of Kirkland Lake.

Some 450 stations were observed in northern Canada with a gravimeter hired from the North American Geophysical Co., Houston, Texas. Traverses were made along the railways between Cochrane and James Bay in Ontario, and between the Pas and Churchill in Manitoba. Between July 1 and August 10, 213 stations were established in north-western Ontario, northern Manitoba and Saskatchewan, in an area of 185,000 square miles within the Canadian Shield between latitudes 50° N. and 58° N., and longitudes 92° W. and 108° W. Transportation in this area was by chartered aircraft. Observations were taken with a vertical magnetometer at a majority of the gravity stations.

A test of the applicability of the gravity and magnetic methods to the location and delineation of mineral deposits in the area was made by the establishment of 220 stations over the East Sullivan sulphide ore body at Val d'Or.

David Dunlap Observatory, University of Toronto
(*Director, Professor F. S. Hogg*)

Radial Velocities.—During 1947 the regular radial velocity programme on the later type stars brighter than 9·0 photographic in the Yale zone 25° to 30° has been continued. Orbits of six spectroscopic binaries have been prepared

for publication by Dr Heard, Miss Northcott and several senior students. Mr Tanner has investigated the criteria for fictitious periods, statistically, for a large number of spectroscopic binaries. His general conclusion is that, while certain interesting cases of alternative periods were found, their total effect on the statistics of such binaries is not significantly large. Dr Heard continued investigating β Canis Majoris stars, and Professor Yü the spectra of certain irregular variables.

Globular Clusters.—Dr Helen Sawyer Hogg has completed an extensive bibliography of individual globular star clusters. Photographs of clusters for variable star studies have been made with the 74-inch and 19-inch reflectors.

Miscellaneous.—Dr Williamson has been engaged in the integration of equilibrium equations in stellar models for the fainter stars of the main sequence. He has also served as an adviser to the United States Navy—Cornell University microwave-astronomy project. In Vol. **1**, Nos. 7 and 8 of *Navigation*, Dr Heard has investigated the problem of minimum time routes in aerial navigation.

During the year a stellar photo-multiplier type photometer has been constructed for use with the 19-inch telescope. *D.D.O. Pubns.* No. 20 (concluding volume 1), and *Contributions* Nos. 13, 14 have been published. Mrs Hogg has published a regular section "Out of Old Books" in the monthly *Journal of the Royal Astronomical Society of Canada.*

Union Observatory, Johannesburg
(*Union Astronomer, Dr W. H. van den Bos*)

With the 26½-inch refractor 1039 micrometer measures, 6 interferometer measures and 35 plates of double stars were obtained; 18 micrometer measures of Comet 1947*n* and 7 occultations were also observed.

With the 9-inch refractor 64 occultations were observed. Plates taken with the Franklin-Adams telescope were: minor planets 257, comets 110, miscellaneous 8, making a total of 375 plates.

During December 17 comet plates were taken with the Leiden Rockfeller refractor, as the Franklin-Adams telescope is being overhauled.

During the year 737 visitors were admitted.

Weather permitting, daily counts of sunspots have been made with a 3-inch portable refractor.

There were no changes of staff during the year.

Radcliffe Observatory, Pretoria
(*Director, Dr H. Knox-Shaw, Radcliffe Observer*)

There is little to report. The 74-inch reflector is still without its mirror and spectrograph. The figuring of the mirror was finished during the year. If it cannot be aluminized in England, as indeed seems probable, the mirror will be used with a silver coat until an aluminizing plant can be erected in Pretoria, since it has not been found feasible to send it across the Atlantic for this purpose.

Dr Redman completed the photography of the zone $-52°$ to $-64°$ with the Cape cameras, and also a new series of intercomparisons of the Harvard E regions, before leaving the Observatory in August to take up the Professorship of Astrophysics at Cambridge. Dr Evans finished the construction of a prismatic camera and took some preliminary photographs for the determination of colour temperatures of early type stars. He also contributed to the Society a paper

on the structure of the solar atmosphere. The Director completed his catalogue of the magnitudes of 19,850 southern stars, being a revision of the Harvard photometry.

Nizamiah Observatory, Hyderabad
(Director, Dr Akbar Ali)

Astrographic Equatorial.—Thirty-two repetition plates were taken with the astrographic equatorial during the year. Due to scarcity of supplies of photographic plates from England more plates could not be taken. The survey of double stars in zones $-21°$ and $+36°$ has been completed. Out of the 59 regions common to Hyderabad and Potsdam's *Photographische Himmelskarte* with a difference of epochs amounting to more than 30 years, 25 regions had been compared by my predecessor Mr T. P. Bhaskaran and the results of proper motions were published by him. It is proposed to complete this work by comparing the remaining 34 regions. Two regions were compared by me during the year. The reductions of the Eros plates (1931 opposition) are in progress.

Grubb Equatorial.—The total number of occultations observed during the year was 24. They have been reduced and their results are, as usual, being communicated for publication in *Monthly Notices*. The programme of the measurement of double stars has been continued as before.

Spectrohelioscope.—The routine observations of the Sun with the spectrohelioscope have been continued as before.

Publications.—Two papers containing "Occultations of Stars by the Moon observed at Nizamiah Observatory, Hyderabad, 1946" and "Faint stars with proper motions exceeding $0''{\cdot}15$ per annum in Hyderabad Astrographic Zones List V" were sent for publication in *Monthly Notices*. A VIth list of 50 faint stars with proper motions exceeding $0''{\cdot}15$ per annum in Hyderabad Astrographic zones is ready for publication. Vol. VIII, Part II, dealing with the comparison of the places of stars in the Astronomische Gesellschaft Washington Catalogue with the photographic measures on the plates of the Hyderabad Section of the astrographic catalogue is ready for press.

Future Programme.—The Osmania University has given a grant to the observatory for the purchase of a multiplier tube photometer. It is proposed to attach this photometer to the 15-inch Grubb telescope. Mr Gerald E. Kron, Assistant Astronomer, Lick Observatory, has kindly consented to construct the photometer on the latest design for us. With the help of this instrument it is proposed to do the photometry of southern eclipsing binaries.

Miscellaneous.—The meteorological and seismological work of the department has been continued as usual. The *Seismological Bulletin* No. 1 of the Nizamiah Observatory for 1942–1944 has been printed and is being distributed to the important Seismological stations. Mr U. S. Ragha-Vender Rao retired during the year. Sir Harold Spencer Jones, Astronomer Royal and Professor Shapley visited the Observatory early in 1947 January and gave us the benefit of their advice.

Solar Physics Observatory, Kodaikanal
(Director, Dr A. K. Das)

General.—A noteworthy feature of the year was the visit to this Observatory of Sir Harold Spencer Jones, Astronomer Royal, England and Professor Harlow

Shapley, Director, Harvard College Observatory, U.S.A. Questions relating to the post-war development of the Observatory were discussed with them.

Exchange of spectroheliograms with foreign observatories continued as in the previous year and efforts were made to make up the arrears which had accumulated during the years of war. 972 K flocculus plates for the period 1944 April–1947 September were supplied to the Solar Physics Observatory, Cambridge, 150 *Hα* flocculus and 30 K flocculus plates for the period 1943 January–1944 December to the Meudon Observatory, France and 25 photoheliograms for the period 1943–1946 to the Royal Observatory, Greenwich. The Mount Wilson Observatory supplied 180 *Hα* flocculus, 156 K prominence and 21 *Hα* prominence plates for the period 1945 January–1947 May. 38 K flocculus and 61 *Hα* flocculus positives on film for the year 1941 were received from the Meudon Observatory, France.

Routine Observations.—Weather conditions were generally more favourable for observations than during the previous year. The definition of the solar image before 11 a.m. (I.S.T.) estimated on a scale in which one is the worst and five is the best was two or less on 78 days and four or more on 67 days. The mean value of the definition was 2·7. Systematic observations of the general sky conditions and of the definition of the Sun's image at 08, 09, 10, 11, 12, 14 and 16 hours I.S.T. every day were begun during the year in order to study the suitability of Kodaikanal for coronagraph work. Observations with the photoheliograph, the prominence spectroscope, the spectrohelioscope and the spectroheliograph were continued as usual. Direct photographs of the Sun on a scale of 8 inches to the Sun's diameter were obtained on 304 days as against 292 days in 1946. Spectroheliograms in the *Hα* and K lines were obtained on 292 and 282 days respectively, while K prominence plates were secured on 274 days. Quarterly statements of chromospheric eruptions were sent to Dr L. d'Azambuja of the Meudon Observatory, France and to Mr H. W. Newton of the Royal Observatory, Greenwich.

Sunspots.—The number of new sunspot groups observed during the different months of the year, their distribution in the two hemispheres and the mean daily numbers are given in the following table:—

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
No. of new groups	North	14	17	9	12	18	26	18	12	13	22	18	13	192
	South	18	14	18	22	25	17	14	21	14	20	22	22	227
	Total	32	31	27	34	43	43	32	33	27	42	40	35	419
Mean daily No.		7·9	6·4	7·0	7·8	10·7	8·2	6·6	8·7	8·4	9·1	8·5	6·8	8·1

Compared with 1946 there was an increase of 44 per cent in the total number of new sunspot groups observed during the year; the mean daily number showed an increase of 42 per cent. There was not a single day on which the Sun's disk was free from spots. The approximate mean latitude of the sunspot groups for the whole year was 17° as against 20° in the previous year. About 12 per cent of the total number of spot groups appeared in latitudes higher than 25°.

The outstanding feature of the sunspot activity during the year was the appearance of a giant sunspot group in April which surpassed in area the great sunspot group of 1946 February. The April spot group attained a record areas of 4900 millionths of the Sun's visible hemisphere, as measured on the Kodaikanal

photoheliogram for 1947 April 6. It, however, showed very little activity compared with its predecessors in February and July of the previous year.

Research Work.—A programme of experimental study of the motion of matter in and around sunspots was commenced with the H and K lines, using a Littrow prism spectrograph giving a dispersion of 0·45 A./mm. in this region. Plates obtained under good sky conditions were measured to obtain quantitative data regarding the width and structure of the lines. For studying the magnetic field of sunspots simultaneously with the motion of matter in sunspots, the spectra of a number of major spot groups were photographed in the green and red regions, using a 20-ft. grating spectrograph. To study the variation of the effective temperature of the photosphere along a radius with the help of the *CH* bands, spectrograms of the *CH* bands in a carbon arc in an atmosphere of hydrogen were obtained simultaneously with the solar *CH* bands. During the year systematic observations of the heights of prominences in $H\alpha$, D_3 and $H\beta$ were made visually with the prominence spectroscope, and the values obtained were compared with the heights of the same prominences in K line from the spectroheliograms. On the average the visual observations gave smaller values for the heights. The mean heights in $H\alpha$ and D_3 were nearly the same, while the value for $H\beta$ was about 25 per cent less.

Commonwealth Observatory, Mt. Stromlo
(*Director, Dr R. v. d. R. Woolley, Commonwealth Astronomer*)

Solar Work.—Routine sunspot sketches were continued during the year. Registration of 200 megacycle radiation has been continued, together with observations with the spectrohelioscope. In addition, some theoretical investigations connected with the corona have been undertaken.

Time Service.—Transit observations for clock error were secured on 178 nights. Measurements of the personal equations of the observers were made regularly. Rhythmic time signals have been transmitted three times daily from Belconnen Naval Wireless Station, and time signals from WWV, GIA and 3LO recorded nightly. The results have been compared with the Postmaster General's Quartz Clock in Melbourne, and corrections to this clock have been issued regularly.

A determination of the longitude of the transit telescope gave the result $09^h\ 56^m\ 01^s{\cdot}35$ East of Greenwich. This programme was carried out with the cooperation of the Astronomer Royal.

Astronomical Observations.—Observations of position angle and separation of double stars with the 9-inch Oddie refractor were continued, 834 being secured throughout the year. The programme has now been temporarily discontinued and the collected results of 1945–1947 are being prepared for publication. Work on variable stars, using an electron multiplier photometer, has been continued, and progress has been made with preparing the Reynolds 30-inch reflector for a programme of photoelectric photometry and colour temperature determinations. For this, a reflecting slitless spectrograph has been made in the workshop and installed. The dispersion is about 40 A./mm. at $H\gamma$, and the definition is very satisfactory from $H\alpha$ to the Balmer limit. The spectrum of a fifth magnitude star can be secured in five minutes.

Comet 1947*n*.—This object was observed visually and photographically and a preliminary parabolic orbit was calculated.

74-inch Reflector.—Approval has been given for the purchase of a 74-inch reflecting telescope, and some negotiations have been opened with firms in England for the construction and delivery of this instrument.

Miscellaneous.—Work has been continued on the preparation of the Melbourne Catalogue ME 4 for publication.

A plant for aluminizing mirrors has been obtained, with which small mirrors have been aluminized successfully. The workshop has acquired further equipment, including a universal milling machine.

Some progress has been made with the construction of a power drive for the Oddie dome, and also with the construction of a nebular spectrograph, similar to that installed at the MacDonald Observatory in Texas. This has involved the construction of an *f*/1 Schmidt Camera in the Optical shop.

The Observatory derived great benefit from a visit from the Astronomer Royal, Sir Harold Spencer Jones, who gave valuable advice on a number of matters.

Riverview College Observatory, Riverview, N.S.W.
(*Director, Rev. D. O'Connell, S.J.*)

Photographic research on variable stars, which forms the main astronomical activity of the Observatory, has been continued. For some years it had been impossible to obtain an adequate supply of plates, but this difficulty has now been overcome.

Partly reduced observations of occultations have been sent to the Nautical Almanac Office.

Dr J. G. Voûte, former Director of the Bosscha Observatory, Lembang, spent a year at the Observatory, recuperating from the hardships of the war years in Java and preparing his work for publication. He returned to Java at the end of 1947 January, to help in restoring the Lembang Observatory.

The Astronomer Royal, Sir H. Spencer Jones, and the Commonwealth Astronomer, Dr R. Woolley, visited the Observatory in 1947 February.

Publications.—Publication No. 7 was distributed during the year. *Publication* No. 8, containing studies of variable stars, a list of new variable stars and a double star orbit, will be issued shortly.

Sydney Observatory
(*Government Astronomer, Mr Harley Wood*)

The programme of work on the *Astrographic Catalogue* has been continued. Volume 26 was issued and Volume 27 is now in the hands of the printer.

The occultations predicted in the *Nautical Almanac* have been observed when possible, the results for 1946 having been published, while those of 1947 are now being reduced. The programme of visual observations of double stars was continued and measurements are being made of double stars appearing on plates taken for the *Astrographic Catalogue.*

A Marchant calculating machine has been purchased for our computational work.

The Astronomer Royal, Sir Harold Spencer Jones, visited the Observatory on February 24. The discussion with him of the work of the Observatory was very stimulating to us.

The civil work consisting of the supply of astronomical information for legal purposes and time service and answering general inquiries has been carried on. The educational work of the Observatory was continued and lectures and demonstrations on astronomy were delivered regularly.

Carter Observatory, Wellington, N.Z.
(*Director, Mr I. L. Thomsen*)

From February to December the Observatory was open regularly to the public on Friday evenings, when lectures and telescope demonstrations were given. The attendances have been very good and there is considerable public interest in the Observatory.

Observations of sunspots by projection have been made continuously, but owing to staff difficulties the latter half of the year's work has not been reported to the Zürich Observatory. Forecasts of radio disturbances based on solar data have been made to the Post and Telegraph Department and the National Broadcasting Service with at least 80 per cent accuracy. Observations with the spectrohelioscope have been made wherever possible.

Auroral observations have been collected from all sources, as in previous years. A preliminary discussion has been made of the observations for the period 1945 October to 1946 May. A new visual intensity scale has been devised and is in the process of being tested.

Occultation observations made at Wellington, New Plymouth and Dunedin have been collected preparatory to sending to H.M. Nautical Almanac Office.

Equatorial observations were made of Comet 1947*n*, and all New Zealand work on the object has been collected for the purpose of publishing it later.

Mr F. Addey's Observatory
Grove Park, S.E. 12

During 1947, 64 solar disk drawings and 28 drawings of individual sunspots were made. These were forwarded to the Director of the Sun Section, British Astronomical Association.

Owing to removal from Grove Park to Buckhorn Weston, Dorset, observational work was suspended on May 25 and has not yet been resumed.

Mr R. Barker's Observatory, Cheshunt, Hertfordshire

1947 was not a good year for favourable observations. Differences previously observed in the layout and number of the lunar Mersenius clefts were checked. Further evolutionary changes and developments affecting the radial bands on the east wall of Aristarchus were noted. Three hitherto unrecorded clefts have been found north of the lunar Straight Range, but these await confirmation. Much activity of the cloud spots on the equatorial bands of Saturn's globe was observed.

Telescope: 12·6-inch clock-driven Calver equatorial.

Mr J. Evershed's Observatory, Ewhurst, Surrey

The prolonged frost in the early months of 1947, followed by melting snow, caused severe damage to the underground observatory, and no work could be undertaken until the autumn, when repairs had been completed.

High-dispersion solar spectra in the red region were obtained and measured during the last three months of the year; and the results from these, and from two grating plates kindly supplied by the Cambridge Observatory, confirm previous results, in showing a small change of wave-length in certain iron lines compared with similar measures in the year 1940, and with a grating plate taken in Kodaikanal in 1915.

Mr M. B. B. Heath's Observatory, Kingsteignton, Devon

Daylight observations of Mercury were made on 22 days and of Venus on 30 days. Mars was observed on eight nights and Saturn on 19 nights. Determinations of Saturnigraphic latitudes of edges of belts were made on 17 nights and comparisons of satellite magnitudes on 13 nights. Among occasional phenomena observed were the occultation of Uranus, March 1, the occultation of Mars, July 15, and the penumbral eclipse of the Moon, November 28.

Mr F. M. Holborn's Observatory, Streatham, London

During the year 1037 observations were made on 102 nights of 68 variable stars and novae. The Sun was observed on 170 days for spot counts and naked-eye spots. All records were sent to the British Astronomical Association.

In April, the 12¼-inch Newtonian Reflector from Headley Observatory, and on loan from the British Astronomical Association, replaced the former 8½-inch.

Mr B. M. Peek's Observatory, Solihull

The usual planetary observations and the recording of lunar occultations were continued until the end of 1947 July.

In September the observer took up a new appointment in Canterbury and at the end of the year the observatory at Solihull was dismantled. It is hoped that a suitable site for its re-erection will be found before long in Herne Bay, in which case work will be resumed as soon as is practicable.

Mr F. J. Sellers' Observatory, Muswell Hill, London

The principal aim has been daily observations, so far as weather permitted, with the spectrohelioscope. Except for a few days missed near the beginning of the year owing to instrumental adjustments, etc., this programme has been carried out, the Sun having been observed under useful conditions of seeing on 118 days during 1947. Ninety-seven flares, largely of minor intensity, have been recorded, together with dark filaments, prominences and other spectroscopic phenomena. These observations are communicated to Meudon for the *I.A.U. Bulletin* and to Mr J. S. Hey for comparison with radio observations of the Sun; they will also be included in the Summary of Solar Activity to be published in the *B.A.A. Journal.*

The mirrors of the spectrohelioscope were rhodiumized early in the year but, the resulting loss of light being found prohibitive, were afterwards aluminized on the rhodium surface with quite good results. The plano-convex objective has been replaced by a fine achromatic, by Mr F. J. Hargreaves, and some work has been begun on comparing prominence outlines and relative intensities in $H\alpha$ and He (D_3) and dark and bright flocculi in $H\alpha$ and $H\beta$. Other research,

made possible by the stability of focus throughout the spectrum, is in preparation. By means of an achromatic Barlow lens in conjunction with the new objective an excellent image of the Sun (23 inches in diameter and showing the fine detail of spot groups and of the solar surface itself) can now be projected, at any moment while observing with the spectrohelioscope, on a screen near the eyepiece. This has proved of immense value in correlating spectroscopic with telescopic detail and in saving time by obviating the necessity of using the 5-inch equatorial for positioning, etc.

Dr W. H. Steavenson's Observatory, Cambridge

The 30-inch reflector has been used chiefly for the observation of old novae. The results for 1946–1947 have been communicated to the Society.

Measures of the position angles of the four satellites of Uranus, especially Ariel, were made on a number of nights. This work is being continued and the results are being communicated to the United States Naval Observatory, Washington.

Physical observations of comets Bester, Jones, Wirtanen, Reinmuth and Faye were made on a few occasions and the results have been communicated to the Comet Section of the British Astronomical Association.

Mr H. P. Wilkins' Observatory, Barnehurst, Kent

Lunar and planetary work was continued during 1947 with the $6\frac{1}{2}$-inch and $12\frac{1}{2}$-inch reflectors. Owing to its long focus (12 feet) the latter instrument has proved somewhat troublesome in use, the mirror was therefore reground to a focus of 6 ft. 6 in., making the telescope more compact and serviceable.

As the Director of the Lunar Section of the British Astronomical Association, the majority of the observations have been undertaken to confirm, or otherwise, the detail detected by members of the Section and the 10th Report of the Lunar Section was published in October.

REPORTS ON THE PROGRESS OF ASTRONOMY

SOME RECENT APPLICATIONS OF OPTICS TO ASTRONOMY

E. H. Linfoot

The introduction of photography brought considerable changes in the demands which optical systems intended for astronomical research had to meet. Instead of striving for the sharpest possible images over a very small field, the design of a photographic telescope aims at high definition over the whole of a photographic plate. For in visual work, the object under examination can always be brought to the centre of the field of view, whereas a photographic plate records the images impartially over its whole area, which is examined piecemeal after the plate has been developed.

The simple Newtonian telescope illustrates the point. As is well known, a

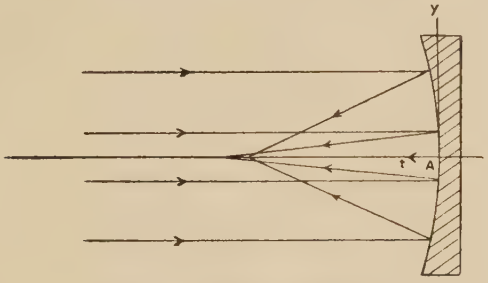

Fig. 1.—*Spherical Aberration.*

simple spherical mirror will not form a sharp image of a star situated on its axis, because the parallel rays meeting the outer zones of the mirror are brought to a shorter focus than those reflected from the parts near its pole A (see Fig. 1). The image is said to suffer from spherical aberration. If the mirror is replaced by a paraboloid touching the original spherical surface at its centre and passing through its edge, this defect is eliminated and the rays are brought to a sharp focus. The change in form of the surface is easily found. On taking Cartesian coordinates t, y in a plane through the axis of the mirror, with origin at the pole A of the mirror surface (see Fig. 1), the surface profile of a spherical mirror of radius of curvature $2f$ is given by the equation

$$(t-2f)^2+y^2=(2f)^2,$$

i.e.

$$4ft=y^2+t^2,$$

which on solving for t in terms of y yields the power series

$$t=\frac{y^2}{4f}+\frac{y^4}{64f^3}+\ldots. \qquad (1)$$

The numerical value of the term in y^4 is very small; in the case of an $f/5$ mirror of 20 inches aperture, it amounts at the edge of the mirror to 1/6400 inch, or about 8 wave-lengths of light. The term in y^6 is in this case less than 1/800 of the term in y^4, and we can safely neglect it, together with all higher terms. Thus the term in y^4 gives the distance, measured horizontally, between the surface of the sphere

of paraxial focal length f and that of the paraboloid of focal length f which touches it at its centre A. A more relevant comparison is with the paraboloid

$$t = \frac{y^2}{4f'}, \tag{2}$$

which touches the sphere at its centre and passes through its edge $y = y_0$. This is (apart from a slight displacement parallel to the t-axis) the paraboloid into which the sphere can be "figured" by optical polishing with the removal of the least possible depth of glass. Subtraction of (1) from (2) gives for the horizontal difference ξ at height y between these two surfaces the equation

$$\xi = y^2(1/4f' - 1/4f) - y^4/64f^3, \tag{3}$$

$$= (y^2y_0^2 - y^4)/64f^3, \tag{4}$$

on making use of the fact that $\xi = 0$ when $y = y_0$ in order to eliminate f'. Now the greatest value of $y^2y_0^2 - y^4 = y^2(y_0^2 - y^2)$ as y runs from 0 to y_0 is assumed when $y = \frac{1}{2}\sqrt{2}y_0 = 0{\cdot}707y_0$, and is $\frac{1}{4}y_0^4$. Hence the "figuring-depth" ξ in the above example is greatest on the zone of radius 7 inches and its value there is about 2 wave-lengths. It is of no practical consequence whether the figuring-depth is measured horizontally, as here, or normally to the mirror surface, since the discrepancy nowhere exceeds one hundredth of a wave-length.

A useful alternative formulation of the same results is made possible by the notion of a wave-surface or wave-front, that is to say, a surface orthogonal to all the rays belonging to a single pencil. In the case of a paraboloid imaging a star on its axis, the wave-surfaces are plane before meeting the mirror, since each is orthogonal to the rays of a parallel beam. After reflection, the wave-surfaces are spheres, since they are orthogonal to rays which meet in a point. The effect of "figuring" the mirror is to deform slightly the wave-surfaces which leave it; removal of a layer of glass δ wave-lengths thick from a part of the mirror surface will retard the wave-surface leaving this part by an amount $2\delta\cos i$, where i is the angle of incidence of the rays on this part. In many practical cases, including the one given above, δ amounts only to a few wave-lengths and $\cos i$ differs from unity by less than one per cent over the whole of the wave-front. We can then say to a sufficient approximation that a figuring-depth δ on the mirror corresponds to a retardation 2δ in the reflected wave-fronts.

Since the figuring (4) will convert the wave-fronts reflected from the mirror into spherical shells, it follows that without this figuring the reflected wave-fronts are distorted from the spherical form in accordance with the retardation function

$$\xi^* = -(y^2y_0^2 - y^4)/32f^3. \tag{5}$$

Here the parameter y identifies the zones of any wave-front by means of the points where the rays through them meet the mirror surface, and y_0 corresponds to the edge-zone.

When a field of stars is photographed at the prime focus of a simple paraboloid, the images close to the axis are good, but those farther out appear as asymmetric, comet-shaped smudges; the system suffers from off-axis coma. For this reason the optical system of the simple Newtonian telescope is not well suited to astronomical photography. The classical Cassegrain system suffers from the same drawback; its off-axis coma is the same as that of a Newtonian of the same focal ratio, and is only smaller in practice because the focal ratio is longer. The first systematic attempt to design coma-free reflecting telescopes appears to have

been made by K. Schwarzschild (**12**). In 1905 he published designs of a two-mirror telescope in which off-axis coma was completely eliminated and the diameter of the useful field brought up to about 3° at an aperture of $f/3$. One of the most successful of his systems is shown in Fig. 2. Both mirrors are "figured", i. e. aspheric. The figurings are, of course, different from that on a paraboloid,

FIG. 2.—*Schwarzschild Aplanatic telescope* ($f/3$).

Off-axis coma can be completely eliminated in any optical system by the use of two aspheric surfaces. For, by the Abbe sine law, the off-axis images will be free from coma of all orders, provided the system satisfies the exact sine condition. In the case where the object is at infinity, this can be formulated as follows. Let PQ denote an arbitrary ray from the axial object point, that is to say, parallel to the axis of the system and at a distance h from it. Let RF denote the same ray after passing through the system; it converges towards the axis, making an angle θ with it, and intersects it in the image-point F. Either of h, θ can evidently be determined from the other by ray-tracing. If, as h and θ vary, the ratio $h/\sin\theta$ remains constant, the system is said to satisfy the exact sine condition.

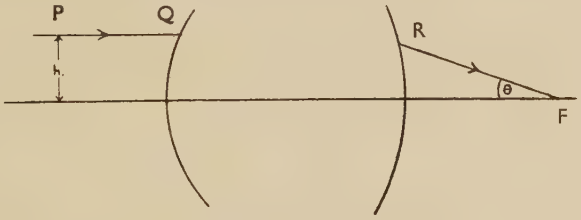

FIG. 3.—*The Abbe sine condition.*

Now consider the special case of a Cassegrain or Gregorian telescope and suppose that we wish to free it from off-axis coma by refiguring the mirrors. A simple iterative method of obtaining the mirror profiles is as follows. Consider a fan of rays traced backwards from the axial focal point F for different values $\theta', \theta'', \ldots$ of the angle θ. Let these rays meet the secondary mirror at the points $R', R'', \ldots$ and the primary at the points $Q', Q'', \ldots$ respectively. By varying the profile-slopes on the secondary mirror, we can adjust the positions of $Q', Q'', \ldots$ until their heights above the axis are respectively proportional to $\sin\theta', \sin\theta'', \ldots$. Then by changing the profile-slopes on the primary we can secure that the rays leave the primary parallel to the axis. Thus we have two profile-change functions, numerical integration of which yields, to a first approximation, the figuring on the mirrors. This first approximation is already accurate to a small fraction of a wave-length in most practical cases, since the effects of the changes in position of the points $Q', Q'', \ldots R', R'', \ldots$ due to the figuring are very small in comparison with the effects of the changes in surface-slope at these points. A second iteration may be needed in the case of wide-aperture systems, however, to ensure that the sine condition is satisfied to six-figure accuracy.

When the system is more general, the computations may be more laborious, but the method and the conclusion are the same; by varying two of the surface

profiles, we can ensure that the backward-traced rays leave the system both in the proper directions and at the proper heights, and hence can obtain axial stigmatism together with satisfaction of the exact sine condition.

Two-mirror aplanats are the simplest type of telescope which can be strictly coma-free, and it is rather remarkable that Schwarzschild's designs did not attract more attention. Only two examples appear to have been put into use; one, of 24 inches aperture, at the University of Indiana and the other, of 12 inches aperture, at Brown University, U.S.A. G. W. Ritchey (**9**) mentions that he constructed the optical parts of a Schwarzschild system in 1923. At about the same time, Richey and Chrétien devised improved types of coma-free two-mirror telescope, more practicable than Schwarzschild's because of their smaller overall length, which stand in the same relation to the Cassegrain telescope as do Schwarzschild's designs to the Gregorian.

An important step forward in astronomical optics, and one of an entirely novel kind, was made by Bernhard Schmidt in 1930 when he introduced the new type of optical system which bears his name. Schmidt was a remarkable and interesting personality. He was born in 1879 on Nargen Island in Esthonia, and R. Schorr (11) in his biographical note on Schmidt records that he attempted as a boy to make a concave mirror by grinding together the lower parts of bottles with sea-sand from the beaches of Nargen. Later, he studied engineering in Götenburg and Mittweida and about 1900 began to make telescope mirrors of outstanding quality for amateur astronomers. In 1905 he executed with extraordinary accuracy and in the short space of three months an $f/2{\cdot}26$ paraboloid of 40 cm. aperture for the Potsdam Astrophysical Observatory. Schmidt carried out his optical work with the simplest means, using relatively thin glass tools for fine grinding and polishing and working all surfaces by hand—with his left hand, indeed, for he had lost his right arm in an accident in early youth. When making a Cassegrain system, he would usually leave the primary mirror spherical and remove the spherical aberration by figuring the convex secondary mirror.

In addition to being an outstanding optician and a first-class engineer, Schmidt was an enthusiastic astronomical observer, and during the latter part of his life he was a voluntary worker at the Bergedorf Observatory near Hamburg. He showed much ingenuity in the construction of mountings and drives for his telescopes; two of his novel mountings were installed at Bergedorf and one at Breslau Observatory.

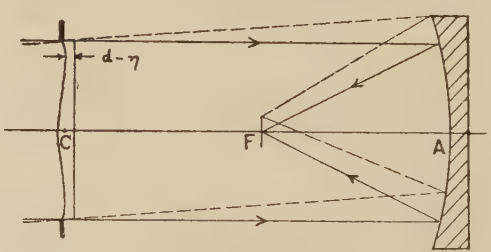

FIG. 4.—*Schmidt Camera.*
(The deformation of the aspheric plate surface is exaggerated about 100 times.)

Schmidt's crowning achievement, however, was the invention of his "lichtstarkes, comafreies Spiegelsystem", now known as the Schmidt camera (**10**). It consists of a spherical mirror together with a nearly plane-parallel figured plate situated at the centre of curvature of the mirror, as shown in Fig. 4. The mirror is

larger than the plate, in order to receive the off-axis pencils. The field surface is curved, and is concentric with the mirror. The object of the plate is to "pre-correct" the wave-fronts in the parallel pencils entering the system so that they may be spherical after reflection by the mirror, and so converge to a sharp focus. Consider first the axial pencil. By equation (3) above, the amount of pre-correction required at the zone of parameter y is a retardation

$$2\xi = 2y^2(1/4f' - 1/4f) + y^4/32f^3, \tag{6}$$

approximately. For 2ξ is, to a good approximation, the amount by which the reflected wave-fronts are pushed forward, on the y-zone, in advance of the desired spherical form. Since the optical path distance through a plate of thickness d and refractive index n is nd for rays entering normally, it follows that this retardation (**6**) will be obtained if one surface of the plate is figured to the profile

$$\eta = \frac{2\xi}{n-1} = \frac{y^2}{n-1}\left(\frac{1}{2f'} - \frac{1}{2f}\right) + \frac{y^4}{32(n-1)f^3}; \tag{7}$$

here η denotes the "figuring-depth" on the plate surface *) and y the parameter of the plate zone, i. e. the distance from the axis at which the rays through this plate zone meet the mirror surface. Because the rays are still very nearly parallel to the axis, it is permissible in the present approximation to take the parameter y as equal to the radius of the plate zone. Then the Cartesian equation of the aspheric plate profile can be written in the form

$$\eta = (y^4 - ay_0^2y^2)/32(n-1)f^3, \tag{8}$$

where y_0 denotes the radius of the edge-zone of the plate and the constant

$$a = \frac{32f^3}{y_0^2}\left(\frac{1}{2f} - \frac{1}{2f'}\right) \tag{9}$$

can be varied at will by varying the value of f', which, it will be remembered, is merely the focal length of the chosen reference-paraboloid. The *strength* of an aspheric plate is defined as $(n-1)$ times the coefficient of y^4 in its surface profile; thus it is independent of a and is $1/32f^3$ in the case of the Schmidt camera.

From Fig. 4 it will be seen that, in order to determine the image errors at an angular distance ϕ from the centre of the field, it is sufficient to calculate the effect on the axial image of tilting the plate, together with the aperture stop S, through an angle ϕ about an axis through C parallel to the plane surface of the plate. Taking Cartesian coordinates x, y in the plane of the aperture stop, with origin at its centre C, suppose that the plate is tilted through an angle ϕ about the axis Cx. The plate thickness $T(x, y) = d + \eta$ is very nearly constant and the slopes $\partial T/\partial x$ and $\partial T/\partial y$ of its aspheric surface in the x and y directions are very small, so that their squares can be neglected.

Now consider a ray, initially parallel to the axis of the system and passing through the point x, y of the aspheric plate surface. The angular deviations which this ray receives from the untilted plate amount to

$$(n-1)\partial T/\partial x, \qquad (n-1)\partial T/\partial y$$

radians in the x and y directions respectively. These deviations produce an error-free axial image, and it is the changes which they undergo when the plate is tilted which give rise to the off-axis aberrations. Two main factors operate to

* That is, the thickness of glass which, laid on to a plane surface, would produce the required asphericity.

produce these changes. In the first place the tilted plate is traversed obliquely by the rays, and this increases the angular deviations associated with each point (x, y) of the plate surface. The new values are given, when $\sin^4\phi$ is neglected, by the expressions

$$(n-1)\frac{\partial T}{\partial x}\left(1+\frac{1}{2n}\sin^2\phi\right), \qquad (n-1)\frac{\partial T}{\partial y}\left(1+\frac{n+1}{2n}\sin^2\phi\right). \tag{10}$$

In the second place, owing to the tilt of the plate, a point (x, y) of the aspheric surface now transmits light to the point of the mirror surface which formerly received it from, approximately, the point $(x, y\cos\phi)$. This causes a further change, of amount

$$(n-1)\frac{\partial^2 T}{\partial x \partial y}(1-\cos\phi), \qquad (n-1)y\frac{\partial^2 T}{\partial y^2}(1-\cos\phi), \tag{11}$$

in the angular deviations. We therefore obtain for the leading terms in the components of angular aberration in the ray through the point (x, y) of the entry pupil the expressions

$$(n-1)\sin^2\phi\left(\frac{1}{2n}\frac{\partial T}{\partial x}+\tfrac{1}{2}y\frac{\partial^2 T}{\partial x \partial y}\right), \quad (n-1)\sin^2\phi\left(\frac{n+1}{2n}\frac{\partial T}{\partial y}+\tfrac{1}{2}y\frac{\partial^2 T}{\partial y^2}\right), \tag{12}$$

where

$$\begin{aligned} T = T(x,y) &= d+\eta([x^2+y^2]^{\frac{1}{2}}) \\ &= d+\frac{1}{32(n-1)f^3}\{(x^2+y^2)^2-ay_0^2(x^2+y^2)\} \end{aligned} \tag{13}$$

is the plate thickness at the point (x, y).

This analysis, due to Carathéodory (**4**), shows that the off-axis errors of the Schmidt camera are very small and are of a symmetrical character. Their symmetry (or rather that of their leading terms) follows at once from (12), (13). To estimate their size in a practical case, consider an $f/3{\cdot}5$ Schmidt camera working over a 6° diameter field. The greatest aberrations are at the edge of the field and are provided by the points $(0, \pm y_0)$ on the boundary of the aperture; by (12), (13) they are

$$0, \pm\sin^2 3^\circ\left[\frac{n+1}{2n}\frac{1}{8}\left(1-\frac{1}{2}a\right)+\frac{1}{16}\left(3-\frac{1}{2}a\right)\right]\frac{y_0^3}{f^3},$$

where y_0/f is equal to $1/7$ in an $f/3{\cdot}5$ system. If $n = 1{\cdot}5$ and if we set $a = 3/2$ so as to minimize the axial colour-spread of the system, as explained below, this expression has the values

$$0, \pm 1/750{,}000;$$

that is, the deviations amount to $\pm 4/15$ second of arc. In an $f/3{\cdot}5$ camera, therefore, the off-axis image-spreads run up to approximately 0·5 second of arc at the edge of a 6° diameter field.

In the discussion given earlier of the "figuring" of a sphere into a paraboloid, the parameter value $a = 1$ was singled out as reducing the overall figuring-depth to its least possible value. Such a value of a would not be adopted by the practical mirror maker; he would use a value near to 2. For it is easier to control the figure of a mirror near its centre than near its edge, and parabolization with $a = 2$ can be effected by polishing away glass on the inner parts of the mirror, leaving the edge zones almost untouched (see Fig. 5).

In choosing the value of the parameter a for Schmidt plates, ease of construction is no longer the chief consideration. The colour-error of the plate is large enough to attract attention in some systems; in such cases the value of a is chosen so as to minimize this colour-error. With a low-dispersion crown glass plate, the angular colour-split over the spectral range F–C may be taken as 1/60 of the greatest

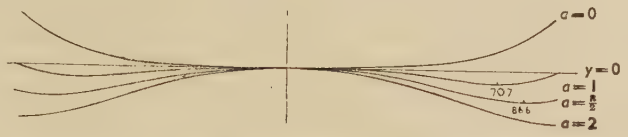

FIG. 5.—*Aspheric profile shapes corresponding to different values of the parameter a.*

angular deviation imposed by the plate. By (8), this deviation

$$(n-1)d\eta/dy=(y^3-\tfrac{1}{2}ay_0^2y)/8f^3.$$

The greatest value of $|y^3-\frac{1}{2}ay_0^2y|$ in the range $0\leqslant y\leqslant y_0$ is taken either at its stationary point $y=y_0(a/6)^{\frac{1}{2}}$ or at $y=y_0$. At the former its value is $2y_0^3(a/6)^{\frac{3}{2}}$; at the latter $(1-\frac{1}{2}a)y_0^3$. If $a=3/2$, these are both equal to $\frac{1}{4}y_0^3$. Hence the angular colour-spread (F–C) of the plate is least when $a=3/2$, and its value in this case is

$$\frac{1}{60}\cdot\frac{1}{8f^3}\cdot\frac{1}{4}y_0^3=\frac{1}{15{,}360F^3}\text{ radian},$$

where $F=f/2y_0$ is the focal ratio of the camera.

For example, in an $f/3{\cdot}5$ Schmidt camera with $a=3/2$, the angular colour-spread (F–C) of the plate is

$$\frac{1}{15{,}360}\left(\frac{2}{7}\right)^3\text{ radian}=\tfrac{1}{3}\text{ second of arc},$$

approximately, and the diameter of the colour-confusion circles in C-light, when the plate is correctly figured in F-light, is approximately $\frac{2}{3}$ second of arc.

The first Schmidt camera, constructed and put into use by its inventor at Bergedorf in 1930, was an $f/1{\cdot}75$ system with a correcting plate of 36 cm. aperture. The mirror was 44 cm. in diameter. Photographs, taken on curved film, gave completely round stellar images over a field 16° in diameter. Later, Schmidt made a second camera, of 60 cm. aperture and 3 metres focal length, together with a parabolic mirror of the same aperture and focal length, and mounted them as a double reflector in an English mounting at the Bergedorf Observatory. The drive was a novel one of his own devising: it employed a lever arm 2·4 m. long, the end of which rested freely against a rotating worm wheel. Schmidt was engaged in the adjustment of this instrument during his last days; he died in 1935.

The central obstruction of the Schmidt camera by its own field-surface restricts the field-size at a given aperture-ratio. If the permissible linear obstruction ratio is $1/k$ the maximum angular field diameter which can be obtained at a focal ratio F is $60°/kF$ approximately. Thus the angular field-size of an $f/3{\cdot}5$ camera must not be greater than 6° if the obstruction ratio is not to exceed $\frac{1}{3}$, and in a Schmidt camera with a 15° field intended for search photography the focal ratio must be at most $f/1{\cdot}33$ if the obstruction ratio is to be kept as low as $\frac{1}{3}$. Schmidt's first camera, working at $f/1{\cdot}75$ over a 15° field, had an obstruction ratio a little less than 0·4. The Schmidt optical system does not satisfy the exact sine condition, but the variation in $h/\sin\theta$—about one part in 250,000 at an aperture

of $f/1{\cdot}75$—is so small that the symmetry of the photographic images is not visibly affected.

At apertures approaching $f/1$, the term in y^6 in equation (1) is no longer negligible, and a term in y^6 needs to be included in the equation (7) for the plate profile. At the still higher apertures, $f/0{\cdot}7$ or more, employed in Schmidt spectrograph cameras, further terms need to be included; alternatively, the plate profiles in such cameras may be determined by numerical integration, starting from a fan of rays traced back from the axial focus as far as the plate, or by means of the exact formulae recently given by Wolf and Preddy (**17**). Still faster cameras for spectrographic work are provided by the solid Schmidt system, shown in Fig. 6A, in which the space between corrector-plate and mirror is filled with a solid block of glass. The solid Schmidt, constructed in glass of refractive index n, is n^2 times faster than the ordinary Schmidt of similar dimensions, and effective speeds of $f/0{\cdot}35$ are practicable in small sizes. Its astronomical usefulness is restricted to spectroscopy, since the initial refraction into the glass is accompanied by dispersion, resulting in a chromatic difference of magnification. The glass is cut away behind the field surface to allow access to the photographic film, which is oiled on to the spherical field surface.

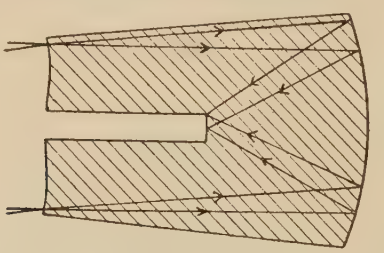

FIG. 6A.—*Solid Schmidt Camera.*

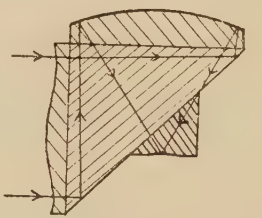

FIG. 6B.—*Folded Solid Schmidt.*

The inconvenience of having the field surface in the middle of a solid glass block was overcome in an elegant and ingenious way by Hendrix (**6**) in his folded solid Schmidt, shown in Fig. 6B. Here the aspheric first surface and the mirror are cemented to the perpendicular faces of a right-angled prism; a smaller prism cemented to the centre of the diagonal face carries the field surface.

Flat-fielded modifications of the Schmidt camera.—In a large Schmidt camera, the inconvenience of the curved field is not very serious provided the angular field size is not too great. Thin glass photographic plates, cut into disks, can be held pressed against a spherical backing-surface during exposure by a retaining ring round the edge; on removal from the holder the plates spring flat again.

Nevertheless, the problem of flattening the field of the Schmidt camera without too much loss of optical definition has attracted a good deal of attention. One method of achieving this is to insert a thin plano-convex lens just in front of the field surface, its plane face in contact with, or very close to, the photographic plate. This flattens the field, by compensating the Petzval curvature of the mirror, at the cost of introducing a little coma into the off-axis images. The coma is small enough to be tolerated in small and medium-sized systems of apertures not exceeding $f/3$.

Another modification, which obtains field-flattening by the old method of introducing off-axis astigmatism, was worked out independently by Väisälä (**14**) and by F. B. Wright (**15**) about 13 years ago. In the best-known example of this type, commonly called the Wright camera, the strength of the corrector-plate is

doubled and its distance from the mirror halved, while the mirror is given a deformation of figure equal and opposite to that which would parabolize it. The short overall length of the Wright camera is an advantage in practice, and the geometrical images are, to a first approximation, uniformly lit circular disks. However, the useful field is rather small; at an angular distance θ from the axis, the diameter of the astigmatic confusion-disks is $\frac{1}{4}A\theta^2$, where A is the linear aperture of the camera. If $f = 50$ inches, $A = 17$ inches, $\theta = 1°$, the diameter of the confusion-disk is 1/850 inch. Thus a 17-inch $f/3$ Wright camera will give first-class definition only over a $1\frac{1}{2}$-inch diameter field. Its image-spreads are approximately five times those of the corresponding Schmidt camera and its colour-error twice as large, but still negligible. It is of course a good deal harder to make than a Schmidt camera.

More recently, systems based on the idea of flattening the field of the Schmidt camera by the addition of a convex secondary mirror have been investigated by J. G. Baker (**1**), C. R. Burch (**3**) and the writer (**7a**). It is an immediate consequence of third order optical theory that the field cannot be flattened without serious loss of definition unless the Petzval curvature of the primary is compensated; a convex secondary mirror of very nearly the same radius of curvature as the primary provides this compensation, and it is then a question of redesigning the system so that its first three Seidel errors, namely spherical aberration, coma and astigmatism, are reduced to negligible amounts. (In large systems, the further refinement of retaining small traces of these errors to set against the higher-order errors is worth while.) The resulting system, shown in Fig. 7, is known as a Schmidt-Cassegrain camera.

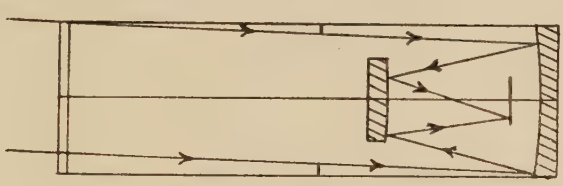

FIG. 7.—*Schmidt-Cassegrain Camera.*

The method of plate-diagram analysis, devised in 1941 by C. R. Burch (**3**), is particularly well adapted to the discussion of systems of this kind, since it provides an intuitive picture of the manner in which the Seidel errors of the system depend on the spacings of the components and the figurings on the mirrors. The method may be explained as follows. First consider the Seidel errors of an ordinary Schmidt camera, which has a stop at the centre of curvature of a spherical mirror and a corrector-plate filling the stop-aperture. This system is not only aplanatic (free from spherical aberration and coma) but also anastigmatic (free from off-axis astigmatism). Hence, by a general theorem in Seidel optics, it remains anastigmatic under an arbitrary shift of the stop, the plate being left in position. We can say that the Schmidt camera consists of a concave sphere provided with an anastigmatizing plate and a stop on the plate. In the case of a Schmidt system designed to work at a finite distance, the strength of the plate (measured by the coefficient of y^4 in equation (6); it can be shown that the term in y^2 may be ignored in a discussion of the Seidel errors of the system) will be changed, since the spherical aberration varies with the working distance, but when placed at the centre of curvature, it still anastigmatizes the sphere. A compound system made

up of a sequence of Schmidt systems (each designed for the appropriate working distance) would be anastigmatic, since each intermediate image would be formed anastigmatically from the previous one.

In the plate-diagram analysis of an optical system S, we represent it as a sum of spherical surfaces, each furnished with an anastigmatizing plate, together with a "plate system" which takes account (i) of the fact that the surfaces are not in general provided with such plates, (ii) of any aspherical figurings which may be present on the surfaces, (iii) of any aspherical corrector-plates which may be comprised in the system.

The physical difficulty that light could not, for example, reach the "missing" anastigmatizing plate of a convex reflecting surface is removed when we Gauss-image such a plate through the part of the system which precedes it; this procedure replaces it by a plate, situated in "object space", which has the same effect on the Seidel errors of the system S. The Gauss image of a plate is here defined as follows: its position and lateral size are found by Gaussian optics, while the retardation which it imparts to the wave-fronts passing through it at each point is to be the same after transformation as before. Figurings on the surfaces themselves (if present) are imaged through in the same way into the object space. When (as is here supposed) the object is at infinity, the resulting set of plates, together with the entry-pupil of the system, will reproduce the first three Seidel errors (spherical aberration, coma and astigmatism) of the actual system S. This set of plates, working in parallel light, we call the plate system belonging to S. If $\alpha_1, \alpha_2, \ldots \alpha_n$ are the strengths of the asphericities of the different members of the plate-system and $x_1, x_2, \ldots x_n$ their respective distances (positive against the light) from the entry pupil, the plate-system can be completely described by means of the diagram of Fig. 8, which we call the plate diagram of S. Then it can be shown that the condition that the spherical aberration of S would vanish is $\sum_i \alpha_i = 0$; the condition

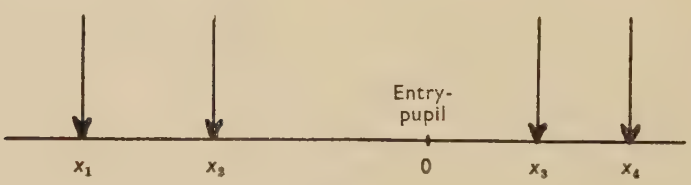

FIG. 8.

that the coma should vanish is $\sum_i \alpha_i x_i = 0$; and the condition that the astigmatism should vanish is $\sum_i \alpha_i x_i^2 = 0$. If the first two conditions are satisfied, then S is aplanatic; if all three, then S is anastigmatic.

In the case of a Schmidt-Cassegrain camera, the components in the plate-system are (i) the glass aspheric plate of the system, (ii) the missing anastigmatizing plate of the primary (with sign reversed, since it is missing), (iii) the figuring on the primary, (iv) and (v) the images, via the primary, of the figuring on the secondary and the missing anastigmatizing plate of the secondary. If the primary is spherical (iii) is absent; if the secondary, (iv).

The general equations now take the form

(Spherical aberration) $$A + B + \Gamma + q^2(2\xi - q)^2/\xi^3 - 1 = 0, \qquad (14)$$

(Coma) $$-\{(1-q)/q\}B + \sigma\Gamma + q^2(2\xi - q)(2\xi + 1 - q)/\xi^3 - 2 = 0, \qquad (15)$$

(Astigmatism) $$\{(1-q)/q\}^2B+\sigma^2\Gamma+q^2(2\xi+1-q)^2/\xi^3-4=0, \qquad (16)$$

where A, B, Γ are the optical figuring-*depths* (fourth-power terms only) on primary, secondary and plate, expressed in terms of parabolic correction of the primary as unit; σ is the distance of the plate in front of the primary, expressed in terms of the Gaussian focal length f_1 of the primary as unit, $1-q$ is the separation between the mirrors, expressed in terms of f_1 as unit, and ξ is the ratio of Gaussian focal length of the secondary to that of the primary.

These three equations specify all the Schmidt-Cassegrain anastigmats, while (14), (15) taken alone specify all the Schmidt-Cassegrain aplanats, in terms of six parameters, each of which has a simple physical meaning. The Ritchey-Chrétien systems are also included, as the special case $\Gamma=0$. The flat-fielded anastigmats are obtained on setting $\xi=1$.

J. G. Baker, who considered only the flat-fielded anastigmats, singled out four types as especially promising; the one with $B=0$, i. e. a spherical secondary, seems to possess some advantages in ease of construction over the others. At $f/3$ its primary is very nearly spherical. The plate strength is greater than that of a Schmidt of the same aperture and focal length, but colour-error is still harmlessly small at this focal ratio.

Of somewhat simpler design than the Baker cameras, and of equal photographic performance in many practical cases, are the flat-fielded aplanats given by (14) and (15) together with the condition

$$\xi q^2(2\xi-1-q)^2=2(1-\xi)\{\xi^3-q^2(2\xi-q)^2\}, \qquad (17)$$

which secures that the "best-field" surface, i. e. the surface halfway between the sagittal and tangential focal surfaces, shall have zero Seidel curvature. The first example of such a system appears to have been given by H. Slegovt (**13**). Their off-axis astigmatism is so small that they are for all practical purposes anastigmatic. Because they involve only one aspheric surface, they are easier to make than the Baker cameras, or than the Wright camera, and give a better optical performance than the latter. They do not satisfy the exact sine condition, and their focal ratio must therefore be kept below the limit at which higher coma becomes appreciable.

In all the Schmidt-Cassegrain cameras, the best field size at a given focal ratio is fairly closely determined by considerations of vignetting and of central obstruction. A system of nominal aperture $f/3$ and central obstruction ratio limited to $\frac{1}{2}$ may work over a field of 5 or 6 degrees diameter; if a larger field is the desired, aperture must also be increased, and when this is done, the colour-error of the plate ceases to be negligible. J. G. Baker (**1**) had pointed out that the difficulty could be overcome by the use of an achromatized corrector-plate, consisting of two figured plates, of different glasses and opposing strengths, placed in contact. In 1944 it was shown by the writer (**7b**) that if the plates are separated somewhat, flat-fielded anastigmatism combined with nearly perfect colour-correction can be obtained with both mirrors spherical. Fig. 9 shows one of these two-sphere two-plate systems; they satisfy the exact sine condition and are easier to make than a Baker camera with achromatized plate, since only two aspheric surfaces are employed.

Meniscus systems.—The success of the Schmidt camera led to the design of lens-mirror systems, employing only spherical surfaces, in which the aberrations of a spherical mirror are compensated by a sharply curved meniscus lens of low power,

placed so that its surfaces are nearly concentric with the mirror surface. This idea, developed independently by D. Gabor, by A. Bouwers (**2**) and by D. D. Maksutov (**8**), makes possible the construction of small and medium-sized astronomical cameras, of performance comparable to that of the Schmidt camera, without the

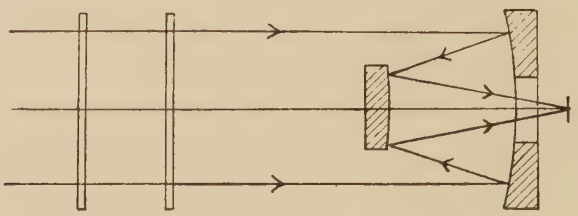

FIG. 9.—*Two-plate Schmidt-Cassegrain system.*

use of aspheric surfaces. Such systems, one of which is shown in Fig. 10, are excellently suited to the requirements of the amateur astronomer, and of schools and colleges. It seems unlikely that they will ever replace large Schmidt cameras in the big observatories, however, because of the practical difficulties involved in the construction and mounting of a large, steeply curved meniscus lens.

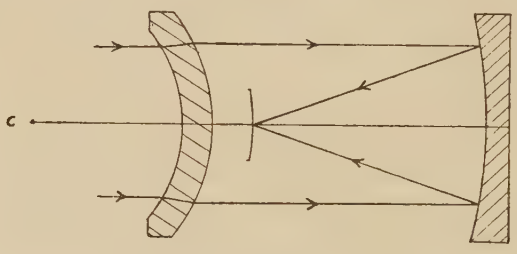

FIG. 10.—*Maksutov Camera.*

Still better optical performance can be obtained by combining in a single system the use of a strictly concentric meniscus and of a corrector-plate analogous to a Schmidt plate (Bouwers (**2**); Hawkins and Linfoot (**5**)). The resulting system is known as a Meniscus-Schmidt system. Since the errors due to the mirror can be reduced, uniformly all over the curved field, to a small fraction of their original size by a proper choice of the meniscus, the deviation from plane-parallelism of the corrector-plate which completes the axial correction is much smaller than in the Schmidt camera. It follows that the off-axis errors, which can be regarded (as in the Schmidt camera) as arising from the tilt of the corrector-plate relative to the off-axis parallel beams, are much smaller than those of the classical Schmidt. Even in an $f/1{\cdot}2$ system working over a 30° field, the aberrations are so small as to set optical glass manufacturers a serious challenge, if the possibilities of the design are to be fully realized in practice. The aspheric profile of the corrector-plate is somewhat different from that in the Schmidt camera; its turn-up edge being a good deal "softer" in outline. Some colour-error is introduced by the meniscus, which acts as a weakly divergent lens, and this is corrected in the design of Hawkins and Linfoot by making the plate in the form of a doublet, with glasses of different dispersions but nearly the same mean refractive index, as shown in Fig. 11.

Finally, mention should be made of the double-meniscus system of C. G. Wynne (**16**). By the use of two near-concentric meniscus lenses, one on either side of the

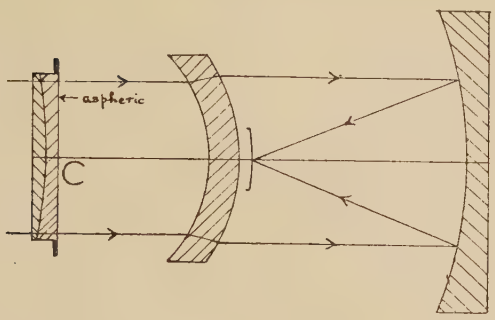

FIG. 11.—*Meniscus-Schmidt Camera.*

centre of curvature of the spherical mirror, an optical performance comparable to that of the Meniscus-Schmidt is obtained without the use of aspheric surfaces. One of Wynne's systems is shown in Fig. 12.

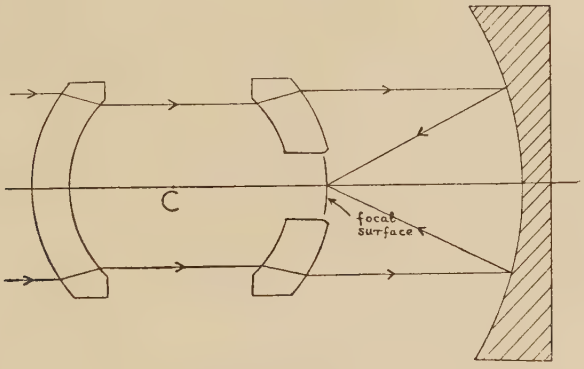

FIG. 12.—*Wynne Double-meniscus system* (*f*/1).

Small systems of this type should be very useful as spectrograph cameras and aurora cameras; medium-sized systems, because of their wide field and high speed, should be of value in astronomical search-photography.

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THE ORIGIN OF THE SOLAR SYSTEM

HAROLD JEFFREYS

To avoid undue repetition of early work, most of which has been amply discussed, I take as starting-point the account in Chapters I–IV and XIV of the 1929 edition of "The Earth". The outstanding feature was the close approach to the Sun of a somewhat larger star; the tidal forces due to the star were supposed to have become great enough to lead to the ejection of a filament of matter from the Sun. This would be gravitationally unstable and would break into pieces, which were identified with the planets. It actually appeared that this instability would arise when the length was not much greater than the thickness (p. 27), so that the formation of the planets would be nearly simultaneous with that of the filament; but it was convenient to discuss the two processes separately. The fragments, probably still only partly condensed, would approach the Sun closely on their first perihelion passage and in suitable conditions might be again broken up, producing satellites. (It appeared, however, that such disruption would require an improbably close approach for the Earth and Mars on account of their probable high density at an early stage, and that it would not explain the retrograde satellites.) Much material, mainly hydrogen, would be lost from the filament and form a resisting medium moving around the Sun, the velocity at any distance being near that of a planet in a circular orbit at the same distance. The resistance of this to the motions of the planets would gradually reduce the eccentricities and inclinations of the orbits; meanwhile, its own viscosity would cause it to be partly expelled from the system and partly to return to the Sun, incidentally giving the Sun a rotation in the same direction as the prevailing orbital motion. The zodiacal light was attributed to the last traces of the medium. The difficulty about the tidal disruption of the Earth, among other reasons, led to the adoption of the resonance theory of the origin of the Moon.

It is now clear that this theory needs substantial modification at every point mentioned, and in some places is completely wrong.

The supposition that the zodiacal light is due to molecular hydrogen made it possible to identify it with the remains of the resisting medium. For an assumed mean density it was possible to estimate the rate of decay of the medium and the time needed to make a substantial reduction of the orbital eccentricity of Mercury. The two should be of the same order of magnitude. The density was adjusted so that this would be the case; this led to an estimated age of the system in reasonable agreement with the estimates provided by radioactivity in rocks, and appeared to provide some confirmation. Serious objection has, however, been made to the hypothesis that the zodiacal matter is gaseous, for if so the light should be strongly polarized, and it is not. The matter must consist of solid particles, large compared with the wave-lengths of visible light, and the argument loses its basis.

In an early paper * I considered the hypothesis that the light came from a swarm of solid particles, and found that the swarm would degenerate on account

* *M.N.*, **77**, 93, 1916.

of collisions in something of the order of 10^7 years. It therefore becomes necessary to provide an explanation of its maintenance.

The resonance theory now appears untenable. It requires a coincidence between the Earth's free period for oscillations of tidal type and the half-period of rotation. The former can be taken as long as two hours if the Earth was fluid. But for a tide, whose equilibrium amplitude would be a few centimetres, to be worked up by resonance to a height enough for instability to set in requires two conditions: damping must be negligible, and so must the terms of higher order neglected in the ordinary theory of resonance, at least in the more usual cases in astronomy. About 1926 it became clear that the Earth has a central core of high density, and in any oscillation while the Earth was fluid there would be a discontinuity of velocity at the core boundary. This would lead to a loss of energy by turbulence at a rate proportional to the cube of the amplitude, and quantitative examination showed that the tidal energy would be dissipated as fast as it was put in when the tide had reached a height of about 20 km., nowhere near enough for instability. Almost immediately afterwards Professor E. W. Brown pointed out to me that departure from linearity of the differential equations would also severely limit the amplitude reached, though he gave no detailed discussion. It appears therefore that the resonance theory must be abandoned, and with it any idea that the Moon has been formed from the Earth by fission. (Moulton had shown long before that the angular momentum of the combined body would not be enough to give rotational fission, and the conclusion is strengthened by allowance for heterogeneity.)

A more general difficulty concerned the rotations of the planets. Direct attraction of external bodies would not produce rotation, by a well-known theorem in hydrodynamics. Vorticity in a fluid can be produced only by diffusion from a sheared boundary or by differences of density over surfaces of equal pressure. The latter can arise from differences of temperature or composition, but do not appear capable of making a whole body rotate in the same direction. It was supposed that the Sun acquired its rotation from the ejected matter falling back into it, which would have acquired momentum from the star; similarly the rotations of the planets were attributed to matter returning to them after disruption by the Sun. On quantitative examination it was found* that to explain the rotations of the outer planets in this way we would require them to have reabsorbed far more than the total mass of their existing satellites. But it appeared that a simple modification of the theory would avoid the difficulty, namely, if the original encounter was an actual collision of the star with the Sun instead of only a close approach. A head-on collision would not do because it would not produce rotation, and a grazing one would not do because it would not remove enough matter. It must be an ordinary collision, say midway between the two. During it, a layer of rapid shearing would form between the bodies and most of the ejected matter would come from it. The hydrodynamical aspect of the matter was treated by rough methods based on those that have been found successful in tidal theory and meteorology. There is some indefiniteness in the result, according to the fraction of the sheared layer that went into the planets; taking this as one half, I found that the theory led to the right orders of magnitude for the total mass of the planets, their rotational angular momentum and the rotation of the Sun. If the fraction was anything between

* *M.N.*, **89**, 636–641, 731–738, 1929.

one half and one, the first two orders of magnitude would not be altered and reabsorption is still available to account for the rotation of the Sun. It appeared that there was at last a theory of the origin of the solar system that made successful quantitative predictions. The treatment could, of course, yield only rough estimates, but previous theories, however elaborate the analysis of parts of them might have been, had been incomplete at some point in such a way that any comparison with observation could only be qualitative.

The apparent success was short-lived. H. N. Russell pointed out* a dynamical inconsistency. The angular momentum of a given particle moving about the Sun depends only on the latus rectum of the orbit, which is necessarily not more than four times the perihelion distance. The perturbing effect of the star would become small when its distance had increased to a few solar diameters, and the distance of the ejected matter from the Sun would be less. Hence the angular momentum of a primitive planet would not be many times what it would be if the planet moved in a circular orbit at a distance comparable with the Sun's diameter. The later effect of the resisting medium would not affect the angular momenta systematically, and Russell drew the conclusion that if collision gave rise to planets at all, their distances would not be many times the Sun's radius; and they are.

Russell suggested a possible escape from the difficulty, without much apparent confidence, but it was followed up by R. A. Lyttleton with some success.† If the Sun at the time of the encounter was a double star, the encounter might be with the companion, and Lyttleton showed that in certain conditions it would be possible for both the star and the companion to escape from the Sun's neighbourhood, while leaving a considerable fraction of the ejected matter revolving about the Sun. On the face of it, the problem looks a quite intractable one of four bodies, but Lyttleton's calculations, though rough, appeared to have a sufficient margin of safety. On this theory the planets could have distances of the order of the distance of the secondary, and Russell's difficulty appeared to be met.

There is a fundamental difficulty in any attempt to explain the origin of the solar system: the masses of the planets together are a small fraction of the mass of the Sun, and yet their distances are so great in comparison with the Sun's radius that their orbital movements carry most of the angular momentum of the system. The nebular hypothesis broke down over this difficulty; the collision theory also broke down, and Lyttleton's theory was the first that showed any signs of meeting it. In view of Russell's objection it seems wildly unlikely that any theory involving the generation of the planets from the Sun when it was anywhere near its present size could be consistent with the planetary distances. To suppose that the Sun was very much distended at the time, as was supposed in Jeans' form of the Tidal Theory, might help a little, but introduces two difficulties. In the first place, the stellar time-scale indicates that at the time of the origin of the Earth, say 2×10^9 years ago, the Sun should have been in practically its present state. In the second, if the radius of the Sun was, say, a quarter of the distance of Neptune, all the planets as far out as Jupiter would have been inside it, and to explain them would need a succession of disruptions.

The promising agreements in order of magnitude also break down on further

* *The Solar System and its origin*, New York, 1935.
† *M.N.*, **96**, 559–568, 1936.

examination. It was natural in the first place to suppose that the mean composition of the planets was somewhere near that of the Sun. But increasing knowledge of astrophysics has indicated that about 99 per cent of the mass of the Sun is hydrogen, and it would be stretching the data to make the ratio in the planets more than 10 per cent. Consequently any theory of the origin of the planets from the Sun or any other star must admit that something like 90 per cent of the matter lost to the Sun or star failed to collect into the planets, and either went into the resisting medium or was lost to the system. The original form of the collision theory indicated that about 1 part in 500 of the mass of the Sun would be swept off; but with allowance for differences of composition and the fact that much of the matter would be lost to both bodies, it is probable that the fraction needed to account for the masses of the planets would be more like 1/20. It is assumed in Lyttleton's theory that the Sun was the larger body; this difficulty would be mitigated if it was the smaller component of a double star, but this suggestion may introduce others. The argument on the age of the system also needs re-examination. The angular momentum of a given mass in a circular orbit increases with distance r like $r^{\frac{1}{2}}$; consequently the dispersion of any non-zero mass to infinity would require infinite angular momentum, as has been pointed out by F. Nölke. The fate of the resisting medium could then only be absorption into the Sun, but if it had several times the mass of Jupiter this would make the Sun rotate faster than it does. Also the part that has been driven outwards should be visible.

There is a still more fundamental difficulty in all catastrophic theories. The belief that an elongated filament would be gravitationally unstable and would break up into a number of pieces rested on an argument of Jeans, which supposed that the filament was in equilibrium. But matter ejected from the Sun or a companion star would be initially at a high temperature, and it is doubtful whether its gravitation would be able to maintain equilibrium. I investigated some special cases*, considering spherical planets, and found that the distension would become enormous, even neglecting inertia, but it seemed possible that adiabatic cooling during the expansion would lead to the formation of liquid drops at an early stage. This might relieve the pressure before the velocities became uncontrollable. A similar suggestion formed part of the theory of Chamberlin and Moulton. A somewhat different approach was made by L. Spitzer†, who took account of the accelerations during the expansion of cylindrical and ribbon-like filaments, and came to the conclusion that either would dissipate completely. He did not consider liquefaction, but he did consider loss of energy by radiation and found that it would have a small effect in the time available, and unless the latent heat could be disposed of there could be little liquefaction. Lyttleton‡ replied that, at the stage considered, the transverse components of the attractions of the stars would be enough to prevent dissipation; but if so, the longitudinal components would apparently make matters worse.

Another problem arose from the compositions of the planets. So long as it was generally believed that the outer planets were very hot, it was natural to attribute their low densities to their being largely gaseous, though even then there were difficulties because the densities of several of the satellites are as

* *M.N.*, **89**, 731–8, 1929. † *Ap. J.*, **90**, 675–688, 1939. ‡ *M.N.*, **101**, 225, 1941.

low. But this explanation is now untenable. I pointed out * that if the surface temperature of Jupiter is comparable with the equatorial temperature of the Earth, it has had time to radiate away any reasonable initial store of heat several times; and I inferred that the present surface temperatures are maintained by solar radiation, like that of the Earth, and should be of the order of 120 deg. abs. Between the publication of these two papers Coblentz and Menzel published the results of direct measurement of the infra-red radiations and confirmed the conclusion that the surfaces of the great planets are intensely cold. The actual total radiation is definitely greater than solar radiation will explain, and the balance may possibly be due to original heat brought up by convection from great depths.† There are conspicuous absorption bands in the spectra, which had not been identified, but with the suggestion available that they might be due to a cold gas instead of a hot one, they were found by R. Wildt to correspond to bands in the spectra of methane and ammonia; and the low densities of these in the solid state were consistent with their forming a considerable part of the bulk of Jupiter and Saturn. Much further work on the constitutions has been done, especially by Wildt; for the present purpose the important point is that the outer planets consist of lighter material than the inner ones. But for the inner planets separately, the order Earth–Venus–Mars–Moon is the order of decreasing size and also of decreasing density. (The astronomical determination of the density of Mercury is very uncertain.) The differences used to be attributed to compression, but a large quantity of geophysical work has led to the conclusion that the effect of compression is much too small to account for the differences in the densities, which must be attributed to differences of composition, and especially to differences in the relative sizes of the metallic cores. The radius of the core in the Earth is a little over half the outer radius, and there are great difficulties in supposing that the Moon has a core of any appreciable size.‡

The greater densities of the inner planets find a natural explanation if they were originally gaseous, for the greater masses of the outer zones would retain lighter materials, which would be lost by the smaller ones. On any theory of gradual evolution we should expect the materials to be thoroughly mixed and the compositions nearly uniform; but the difference is just what we should expect if bodies of different masses were set free suddenly in a vacuum. Thus the difference between the inner and outer planets favours a catastrophic theory. On the other hand, we might expect that the constitutions of the inner planets would be similar as regards materials of high boiling-points; it is hard to see how they could have lost iron in preference to silicates. The facts suggested that the materials had time to separate after they left the parent body; in other words, that they originally formed only one or two bodies, which preserved their individualities while the heavy metals settled to the centres, and were broken up at a later stage.

At the time when this point was noticed, it appeared that all the possible modes of disruption had been examined and found unsatisfactory, but, while looking for something else, I came upon a paper by E. Cartan on the stability of the Jacobian ellipsoids.§ It had been established by Poincaré, Liapounoff

* *M.N.*, **83**, 350–354, 1923 ; **84**, 534–538, 1924.
† *M.N.*, **98**, 214–5, 1938.
‡ *M.N.*, **94**, 823–4, 1934 ; **97**, 3–15, 1936 ; *Geophys. Suppl.*, **4**, 1–13, 62–71, 1937.
§ *Proc. Int. Math. Congr.*, Toronto, **2**, 9–21, 1924.

and Jeans that for a sufficiently high rate of rotation the Jacobi ellipsoids become secularly unstable and that they do not pass into any other secularly stable figure. The ordinary stability had not been investigated, and seems to have been thought unimportant; at any rate, Cartan's solution had passed unnoticed. Lyttleton, however, saw that it was of the first importance to problems of fission. The distinction between ordinary and secular stability arises in gyroscopic systems with small dissipation. If such a system is secularly stable, it is also ordinarily stable, and any small disturbance will be gradually damped out without producing great change in the motion, as for a top hanging downwards. If it is ordinarily stable without being secularly stable, as for a top spinning upright, some small disturbance will increase slowly in amplitude, the rate of increase being slow for small dissipation. The associated damping withdraws energy from the system at an increasing rate, and the motion will change either to some new and secularly stable type of steady motion, or to some unsteady motion. If it is neither ordinarily nor secularly stable, the disturbance will increase at nearly the same rate whether friction is present or not.

It was known that the Maclaurin spheroids are ordinarily stable even at such rates of rotation that they are secularly unstable, but the instability leads to the Jacobi figures, so long as these in turn are secularly stable. Poincaré had shown that these in turn would become secularly unstable with sufficient angular momentum, and that a furrow would develop near one end. Liapounoff and Jeans showed that the pear-shaped figure would be secularly unstable, so that there would be no way of storing the angular momentum except by fission. It was generally supposed that viscosity would be enough to keep the mass in uniform rotation during this process and that the changes would be slow, so that the final result would be two unequal masses with a nearly circular relative orbit. Explanations of close binary stars were offered on these lines. The conclusion, however, depends on the supposition that the system is ordinarily stable. If it is not, there is no reason to suppose viscosity enough to keep the rotation uniform. Cartan had actually proved that when the Jacobi figures become secularly unstable they also become ordinarily unstable. I somewhat modify Lyttleton's argument. When instability arises, the outward motion will be accelerated and not slow; viscosity being unable to keep pace with the changes, the end portion will be subject only to small changes of angular momentum and the angular velocity about the main portion will decrease. Hence the result will not be a circular orbit but a highly eccentric or hyperbolic one.* The former can be excluded, because the detached part would return to its original distance and collide, with further loss of energy. This would make the instability worse, and no permanent solution is to be found on these lines. Therefore, even if the original orbit is not hyperbolic, one will be produced by repeated encounters, and in any case the result will not be a planet and satellite or a binary star, but two bodies moving independently. From considerations of energy and angular momentum Lyttleton estimates the mass-ratio as at least 6 to 1.

The bearing of this result on the formation of planets is twofold. In the original form of the theory of fission due to rotation, the predicted ratio of the sizes of the bodies made it obviously inapplicable to the formation of any satellite except the Moon, and the possibility for the Moon disappeared on closer examination. In the new form a disrupted planet would give two or more independent planets, and it therefore suggests a means of accounting for the differences of

* *M.N.*, **98**, 633–645, 646–650, 1938 ; **101**, 349–351, 1941.

composition among the inner planets. They might have been originally one or two bodies, which acquired too rapid a rotation for stability as they condensed, but the central cores could have had time to form before instability developed. (Non-homogeneity would delay instability, but not prevent it.) Lyttleton goes further by bringing all planets into the scheme, and by arguing that secondary disturbances, like a splash, might be associated with the separation. Some pieces might continue with each of the main bodies, giving satellites, and others might become independent of both bodies, giving the terrestrial planets and the Moon. At least two original planets would be needed, since the mass of Jupiter is less than six times that of Saturn. I think that this theory makes it difficult to see why all the smaller planets (except Pluto, which may well have once been a satellite of Neptune *) are all near the Sun, and should prefer to regard them as having been near the Sun to start with. Lyttleton objects to this that on a catastrophic theory the initial temperature of ejected matter would be of the order of 10^7 deg., and it is doubtful whether anything less massive than Saturn could hold together at that temperature. In any case his suggestion is important.

The rotation suggested is appreciably faster than that of any planet, but not so much as one might have thought. The rotation period of a body of uniform density 1 on the verge of disruption would be 7·2 hours. A nearly spherical body rotating at this rate would be nowhere near instability; but it would have a much smaller angular momentum than the critical Jacobi figure on account of the greater moment of inertia of the latter. In fission the end part would go away, taking away much of the angular momentum in the form of orbital angular momentum. Accordingly, the two parts, when they became separate, may have had rotations not much faster than the critical Jacobi ellipsoid and substantially less than the critical Maclaurin ellipsoid. Nevertheless, they would probably be appreciably faster than that of any planet now. Further, the rate for the actual planets would be greater than for the homogeneous ones considered in his theory. For the inner planets tidal friction is available to bring the rotation down to the present rate (though the slow rotation of Venus presents a difficulty), but not for the outer ones. For these Lyttleton appeals to accretion of the resisting medium, and since this would be largely composed of the lighter materials this process would further reduce the densities of the great planets.

In another paper Lyttleton points out that fission might lead to the formation of a planetary system without the need of an external disturbance. He considers a triple star with two components very close; the third is the Sun. By an extension of Darwin's work on fluid masses with large companions he shows that if the two near components coalesced, the angular momentum would be enough to produce fission and make them separate indefinitely †; the two parts might both escape from the third body while leaving part of the splash to be captured by it. There is no obvious quantitative objection to the theory except the one about the high initial temperatures of the planets, which applies to all catastrophic theories. The coalescence is attributed to accretion of interstellar matter, for which independent evidence is given in a series of papers by F. Hoyle and Lyttleton.

* Lyttleton, *M.N.*, **97**, 108–115, 1936.
† *M.N.*, **101**, 216–226, 1941.

It may appear that on the triple star hypothesis all planetary rotations would be in the plane of rotation of the disrupted body, and that the differences of the inclinations of the axes provide a fatal objection. Lyttleton's answer is that over long intervals of time the inclinations might change considerably. I should doubt this, because I think that such changes could only be consequential on great changes of orbital inclination, of which there is no sign. But the whole process of coalescence and disruption on the theory would be very rapid and it seems quite possible that differences of rotation before coalescence might be partially preserved.

A theory due to Hoyle* bears some resemblance to the triple star theory, but is much more far-reaching. Its main object is to explain the existence of elements of large atomic number. The maintenance of the radiation of stars by the conversion of hydrogen to helium appears now to be well understood, but the temperature needed to synthesize heavy elements is likely to be about 5×10^9 deg., which is far higher than those in the central parts of ordinary stars. It does, however, occur in a supernova outburst. Hoyle's account of the formation of a supernova is essentially that the star collapses when its hydrogen is exhausted and in the collapse attains the requisite temperature; but the conservation of angular momentum will produce disruption during the collapse. If this happened to a component of a binary star most of the later events might be similar to those on Lyttleton's triple star theory. A very similar theory is given by G. B. van Albada.† One noteworthy feature of these two theories is that they do not predict the extreme rarity of planetary systems, as the various encounter theories do. The recent discovery of bodies of something like planetary masses associated with stars would therefore support them. A relevant point, however, is that the age of the universe indicated by the apparent recession of the distant nebulae is comparable with the age of the Earth; in any case it appears that the universe was probably much more tightly packed when the solar system was formed. It has been suggested that the difficulties about angular momentum could be removed by some change in the law of gravitation, giving a general expansion of orbits without corresponding expansion of separate bodies; but if Jupiter was once within a few radii from the Sun and we apply the same argument to the satellites, every satellite would have been inside its primary.

A great difficulty in all theories has been to understand the existence of small bodies. For instance, no solid body composed mainly of silicates and of radius less than about 2000 km. could have held itself together by gravitation when gaseous. ("The Earth", p. 28.) The critical radius is larger for bodies of smaller density, and it seems impossible that any satellite or asteroid can have been gaseous at any time. Lyttleton's fission theory applied to rotating planets offers some hope of an explanation, the fission being supposed to have occurred after liquefaction. But there is an alternative. A liquid or solid body, however small, will grow if immersed in a gas, provided that the density of the gas exceeds the saturation vapour density at the actual temperature; that is why raindrops form. Indeed, if this condition is not satisfied, growth will not take place, however large the body is—all that will happen will be the formation of a region of high density around the body. It is therefore important to know the saturation

* *M.N.*, **106**, 343–383, 1946.
† *Ap. J.*, **105**, 393–405, 1947.

vapour densities for the more important substances at planetary distances and to compare them with the probable original densities of these substances in the resisting medium. This problem has been studied by A. L. Parson.* Using known thermodynamic relations, he finds that even at 273 deg. abs. the saturation vapour density of iron would be of the order 10^{-49} g./cm.^{3}; those of *CaO*, *MgO* and SiO_2 would be lower. For ice the probable values are 10^{-11} g./cm.^{3} at 160 deg. abs. and 10^{-16} g./cm.^{3} at 110 deg. abs. It may be inferred that even with the present density of interstellar matter *Fe*, *CaO*, *MgO* and SiO_2 are all capable of condensing. There is at least no difficulty in understanding cosmical dust. But water, and still more methane and ammonia, would be unlikely to condense near Jupiter and Saturn at the probable densities, say 10^{-15} g./cm.^{3}. It seems most likely that the satellites of Jupiter, Saturn and Mars are loose aggregates of silicates; if made of ice they would probably have evaporated. Triton and Pluto might be ice. The asteroids might also be formed of silicates in this way, but meteorites present a difficulty. They are not loose aggregates, but contain large crystals, and also many of them are wholly or largely composed of free iron, suggesting that they are fragments of a larger body that had time to cool slowly. The stony ones might have been ejected from a volcano of Krakatoa type on a terrestrial planet, but this explanation is not available for the iron ones.

One incidental consequence of Parson's result is that it answers my original chief objection to the Planetesimal Theory, namely, that the small bodies would collide and volatilize one another before they could produce any notable effect on the planets. It now appears that if they did the vapour would at once condense again and form new dust, and the accretion by the planets could proceed. The question of accretion of solid matter by the planets therefore needs re-examination, which has been carried out by Hoyle.† He finds that it would take place at an increasing rate as the planet became larger, and that, in particular, if a condensation once reached the mass of the Earth it would grow rapidly to attain a mass of the order of that of one of the major planets. The Earth, in fact, is rather an awkward size, and it is an argument for Lyttleton's fission theory that it provides an alternative means of its formation. Hoyle argues that the accreted matter would provide a direct rotation, but I do not think that this is proved. It is true that the mean angular velocity in a sphere about a planet would be direct, but there seems to be no reason why the new matter should approach the planet equally from all directions, as he appears to assume. The argument in "The Earth" (pp. 52–56) is indecisive as it stands, and I think that the part of it that depends on Jeans' theorem on the steady motions of assemblies is wrong.‡

An attempt on totally different lines is made by C. F. v. Weizsäcker.§ He starts from a disk-like nebula surrounding the Sun; he finds a steady motion for this similar to what I gave for the resisting medium in "The Earth", except that he makes it more definite by assuming a definite distribution for the departure of the local velocities from those for circular orbits. His process is one of gradual evolution, and may be regarded as an adaptation of Roche's theory to a flat system.

* *M.N.*, **105**, 244–245, 1945.
† *M.N.*, **106**, 406–422, 1946.
‡ *M.N.*, **98**, 59–64, 1937.
§ *Z. f. Ap.*, **22**, 319–355, 1944.

But he departs drastically from any previous investigator at the next step. He maintains that turbulence would arise, and makes an extensive study of its kinematics. He argues that particles of equal mean motion would be associated into vortices, and then works out a type of motion such that the vortices would obstruct one another as little as possible. The motion is something like that in ball-bearings; an integral number of equal vortices would follow one another round a circular orbit, while inside and outside such a ring would be others, the sizes being adjusted to give continuity of velocity at the points of contact. The distances of the planets from Mars to Uranus are found to be consistent with there having been five vortices in each ring; larger numbers are needed to account for other spacings, and the rotation of Uranus naturally presents a difficulty. Direct condensation and accretion are both called into play at the later stages. The argument is rather sketchy in many places. I should say that the point that most urgently needs attention is the inauguration of turbulence; this seems to require that the nebula should be unstable, and the possible types of instability need to be known. Weizsäcker appeals to existing irregularities of velocity in nebulae as a justification, but it is not obvious that these represent anything but original irregularities that have not yet been smoothed out. It is also not obvious that the densities would be enough to control the local relative velocities and permit condensation. On this point it seems more desirable than ever that attention should be given to the hydrodynamical problem of the motion of a gas in the neighbourhood of a planet, the latter describing a circular orbit. The motion due to the Sun alone involves both rotation and shear, and though we know a good deal about the effect of rotation on condensation, we know nothing whatever about that of shear.

A still more recent theory of evolution from a rotating disk is due to K. E. Edgeworth.* This starts from a nebula of galactic dimensions and considers the possible types of instability. It is noteworthy because attention is given to shear; it is pointed out that for four directions near a condensation there is no relative rotation, and it is argued that condensed filaments would form in these directions. The theory is mainly one of origin of stellar systems, but attention is given to the problem of the solar system. The author believes that filaments near the Sun would be absorbed into it, and that the planets were formed at a later stage in the condensation.

It will be gathered that I am not satisfied with any existing theory, but many notable advances have been made in the last twenty years, and the problem is to decide which of them are relevant to the origin of the solar system.

* *M.N.*, **106**, 470–490, 1946.

REVIEW OF COSMOLOGY

H. BONDI

The limited amount of space available has made it necessary to restrict this review to the two principal theories and the background against which they must be considered. Some of the other theories are referred to in the bibliography.

The treatment has been kept highly critical throughout, so as to indicate the gaps rather than the achievements of the current theories.

The writer wishes to express his thanks to Dr G. C. McVittie and Mr T. Gold for many helpful suggestions.

1. The Basis of Cosmology

Experimental science is based on the assumption that the repetition of an experiment will reproduce the original results, and indeed the realm of experimental science is defined by this criterion. The second experiment must be an exact replica of the first one, i. e. all the circumstances must be the same. Now while most external influences can be made exactly the same, there are two which cannot, namely the position and time of performing the experiment. The second experiment will naturally take place later than the first one; it may take place at a different spot on the Earth's surface, and certainly its position with respect to our galaxy will be different. Accordingly our assumption of repeatability is meaningless unless we make the hypothesis that the place and time of performing an experiment have no direct influence on its outcome. It is this fundamental assumption of all experimental science on which the structure of cosmology rests and which, as we shall see, in turn requires a suitable cosmology.

Let us consider the application of this assumption to dynamics, which is an experimental science of particular significance for our investigations. Very early it became apparent that the results of whole groups of experiments could be expressed adequately and concisely in terms of so-called laws of dynamics. Some of these laws were applied to the theory of the motion of the Moon. This was a great step, since the object of the investigation was now no longer the result of a controllable experiment, but an extra-terrestrial body susceptible to admittedly frequent observation. The laws of dynamics, hitherto only established on Earth, had to be assumed to be valid in far larger regions. However, this general validity was claimed only for some of the laws and not for others. Although, for example, all terrestrial experiments had shown the gravitational acceleration to be 32 ft./sec.^{2}, a law of variation, plausible but unproved, had to be assumed. The whole method was characteristic of the sharp distinction drawn between the actual motion of a particle (controllable as in ballistics or merely observable as in astronomy) and the law of motion which governed it.

The law of motion was taken to apply to an infinite number of possible motions, of which the actual one was a particular example, and it was only the law which was supposed to be universally valid, while the individual motion was by no means assumed to be repeated automatically elsewhere.

This division between the law of motion (e. g. the law of gravitation) and the actually realized motion (trajectory of a projectile, orbits of the Earth and the

planets) was the physical expression of the Newtonian formulation of dynamics in terms of differential equations (laws of nature) and initial conditions ("accidental" starting values). This sharp division was natural in a branch of science which tried to distinguish between the common characteristics of the members of a set of repeatable experiments and the peculiar features of the individual members of the set.

It was soon found that there were limitations implicit in this method. While it was found that no contradictions arose if the Newtonian formulation of dynamics was supposed to be correct everywhere at any instant, restrictions had to be placed on the observer's system of reference. He was still given a considerable freedom of choice, but his system had to be a member of a certain set of frames of reference (Galilean systems). In this theory the relative velocity of any two members of this set is constant in magnitude and direction. It was not suggested that two observers, both using Galilean systems, would obtain identical or even similar pictures of actual events occurring, but that they could each perform equivalent experiments and that they would deduce the same laws of nature from these events and experiments.

Considerable changes had to be made in the formulation of these ideas and in particular in the definition of frames of reference in order to include electromagnetic phenomena (special theory of relativity), but the underlying ideas discussed here were not seriously affected.

The general theory of relativity proposed to widen the applicability even further, in that it demanded that all laws of nature should be capable of being put into a formulation universally valid irrespective of place, time, and frame of reference. Owing to the known dynamical effects of acceleration this general validity affected the form of the laws far more than their contents.

Newtonian and special relativity strengthen (and grow out of) the fundamental assumption of the universal validity of terrestrial discoveries. According to them the time and Earth's position and velocity do not bias our experiments at all and gravity and the Earth's acceleration are too small to have appreciable effects. General relativity goes a step further and suggests that these latter effects are not merely negligible but actually non-existent.

Although the principles of Newtonian, of special and even more those of general relativity, were intellectually agreeable, a critical examination revealed that they all became less easy to understand as soon as one tried to apply them to the entire universe. The difficulty which arises is of great significance and will be discussed in some detail.

In any local application of dynamics such as, for example, ballistics, the law of motion does not only cover all the cases corresponding to the various initial conditions but all these cases are supposed to have a real or potential existence. It is taken for granted that any set of initial conditions can be simulated to a good approximation in nature or has even actually occurred. The law of motion is neither too wide nor too narrow; i. e. it covers all existing and possible cases and no others. We must notice here that little or no distinction is made between events which have actually occurred and those which "might have taken place" and can, at will, be made to take place in the future. The fact that the trajectory of a certain cannon ball started with an inclination of 15° to the horizontal instead of 14° is considered to be accidental and insignificant, while the fact that its orbit approximates to a parabola rather than to a hexagon is supposed to be vital,

since the angle could be changed easily in a future shot while the nature of its orbit is unalterable.

In the theory of the solar system we cannot change the orbits of the planets at will, but the large number of existing orbits helps us to extrapolate the "ballistic attitude", and some quantities, such as the mean value of the Earth's distance from the Sun, are supposed to be accidental compared to the fact that her orbit is approximately a conic section.

The "ballistic attitude" cannot, however, be extrapolated so as to apply to the universe. The distinction between impossible and possible, but "accidentally" not realized states, becomes absurd when we have to deal with something as fundamentally unique as the universe. While this point is obvious its consequences are manifold and to some extent obscure.

If the spatial or temporal extent of the universe or the states of motion of its members are in any way limited, then all the principles of relativity discussed above are too wide (too general). If, for example, the old theory of the island universe in an ocean of space were correct, then it would be unnecessary to demand that our laws of nature should apply everywhere. Similarly if all the matter in the universe moved almost uniformly and if no radiation were present the special theory of relativity would be unnecessary.

While there is no logical argument against theories which are too wide, it is generally agreed that such a theory is unsatisfactory and likely to be misleading in physics. If then we postulate that a theory of relativity should not be too wide, then any such theory makes certain demands on the structure of the universe. This is a most interesting point, in view of the distinction we had previously drawn between laws of motion and actual motion. While a theory of relativity as such only makes statements about the validity of the laws of motion, its cosmological implications will to some extent make statements about the actual motion of matter in the universe.

While this construction of the cosmological counterpart of any theory of relativity is a logical process which is usually not put into mathematical form, it is likely to lead to mathematical consequences of great importance for the theory. For it may happen that the mathematical treatment of the corresponding theory of gravitation, if applied to the entire universe, leads to divergences which destroy the self-consistency of the theory. We have therefore constructed a test which will automatically exclude some theories from further consideration.

The next step must be a comparison between the logical sequence outlined above and observation. We have started with the fundamental assumption of the irrelevancy of the place and time at which an experiment was carried out. This assumption has to be augmented by a principle of relativity in order to include moving observers. The Michelson-Morley experiment forces us to accept the special theory of relativity, the equivalence of inert and gravitating mass strongly suggests a geometrical formulation of dynamics, such as is given by the general theory of relativity. All these theories and, in fact, our fundamental assumption, compel us to demand a far more homogeneous structure than observation of our astronomical neighbourhood (solar system, galaxy) seem to supply.

It was only when Hubble's observations of extragalactic nebulae opened out new and far vaster regions of space, that it became possible to believe that we were looking at a fair sample of the universe, which was homogeneous on the

large scale. Comparison is usually made between the macroscopic homogeneity of, say, a body of gas and the non-homogeneous nature of its molecular composition on the one hand, and the theoretical homogeneity and the galactic structure of the observed part of the universe on the other. While this comparison seems to be attractive and most cosmologies consider the large scale homogeneity of the universe to be proved, a critical study of the data shows that the tendency of nebulae to form clusters is extremely great and makes the comparison lose at least some of its force.

On the most usual assumption then, the universe is homogeneous on the large scale, i. e. down to regions containing each an appreciable number of nebulae. The homogeneity assumption may then be put into the form: an observer situated in a nebula and moving with the nebula will observe the same properties of the universe as any other similarly situated observer at any time.

In this form the universe is homogeneous in space and stationary in time. However, although according to general relativity the laws of nature are immutable, it cannot in its current form provide a universe which is both homogeneous and stationary. Homogeneous models exist, but they cannot be stationary unless they are void of matter and radiation.

If we drop the stationary condition, homogeneity becomes much more difficult to define, since our two observers have to look at the universe at equivalent times. Hence it is necessary to introduce a "cosmic time". As will be seen later, other reasons can be found for introducing this cosmic time, which at first sight seems to contradict the spirit if not the letter of relativity.

Kinematical relativity also accepts this idea of cosmic time, but gives it even more significance than general relativity does, in that it allows and indeed demands that physical laws and the constants of nature depend on it explicitly.

In the present state of knowledge it seems that all theories divide sharply between space and time, demanding space to be homogeneous on a large scale, but allowing time to be of direct physical significance, though the theories vary in the extent to which they allow cosmic time to affect world conditions.

Summing up our discussion we may say then that the aim of cosmology must be to unify the following three fields:—

(i) Observations of distant nebulae (these will be discussed in the next section).

(ii) The results of terrestrial laboratory physics and of local astronomical observations (solar system and our own galaxy), including the basic principles of relativity.

(iii) The general assumptions about the universe which are a logical consequence of the principle of relativity adopted.

Evidently the most uncertain proposition in all this is the principle of relativity and its attendant cosmological principle. One can approach the problem either by extrapolating from laboratory physics to form a comprehensive mathematical theory of relativity first and consider its cosmological implications only afterwards or, alternatively, one may try to postulate a rigorous cosmological principle and attempt to derive the corresponding theory of relativity and gravitation afterwards. The first procedure was adopted by the school of general relativity, the second by Milne and his followers in kinematical relativity.

A more detailed discussion of these theories will be given in the subsequent sections.

2. The Observational Evidence

The subject of cosmology is, as was indicated in the previous section, closely connected with the astronomical observations of extragalactic nebulae. The identification of the realm of the nebulae with the universe of cosmology is now generally accepted. However, this identification is such a vital step in the development of cosmology that it will be discussed briefly at the end of this section. Until then we shall merely say, that if any observational material has any bearing on cosmology, then the observations of the most distant objects must be of most interest and accordingly we shall give a brief account of the results of these observations.

Observations of the sky reveal that in addition to well-defined stars there are luminous patches with ill-defined boundaries. These objects are named nebulae.* As the aperture of the telescope and the length of exposure of the plate are increased, the number of nebulae observed rises sharply, while some of the previously observed ones are resolved into systems of innumerable stars superposed on an unresolved luminous background.

The observations reveal the following information about nebulae:—

(i) Position in the sky and apparent luminosity.

(ii) Shape.

(iii) Spectrum.

(iv) Information about individual stars in the more or less resolved nebulae.

The parallax of nebulae is, without exception, too small to be detected.

As for (i), the position and apparent luminosity can be observed whenever the nebula itself is observable. With existing apparatus a nebula will be observable over a large part of the sky if it is brighter than apparent magnitude 21·5. Vast numbers of nebulae have been observed and a statistical examination of the data show that the distribution of nebulae over the sky differs markedly from an isotropic distribution. However, the deviation varies in such a way that it can be easily and amply explained as being due to galactic obscuration. (It will be seen that nebulae are extragalactic objects.) We may therefore say that the observational evidence is fully compatible with the assumption of an isotropic distribution of nebulae.

The distance of nebulae can only be measured by comparing the apparent luminosity of a nebula, or a star in it, with its absolute luminosity (if known). In the case of the nebulae brighter than the 13th magnitude (apparent), which are well resolved and show Cepheids, use can be made of the period luminosity relation for the Cepheid variables, to determine the absolute luminosity of the Cepheid and hence to measure its distance. Other, not quite so accurate, methods are supplied by observing the brightest stars and novae in these nebulae and using the absolute luminosity of such stars as given by observations in our galaxy.

These distance measurements (which are confined to the brightest nebulae) give a good deal of valuable information. They show that with a handful of exceptions all nebulae are far outside our own galaxy, the distribution of nebulae in depth is statistically uniform and that, although the absolute luminosity of nebulae varies a good deal, averages are well maintained. Accordingly, nebulae themselves can be used as standard sources of known absolute luminosity, although

* The term "galaxies" is also in common use instead of "nebulae", which latter term is used here exclusively for extragalactic objects.

averages have to be taken to obtain results of reasonable consistency. The main criterion for the distance of the fainter nebulae is therefore simply their own apparent luminosity.

For reasons which will become apparent later it is advantageous, at least in the case of the most distant nebulae, not to translate observed apparent luminosities into hypothetical distances but rather to stick to the direct observational result, the apparent luminosity. For nebulae brighter than the 18th magnitude the derived distances correspond to a uniform distribution; for fainter nebulae certain deviations appear which are of great significance and will be discussed later.

Although, as has been indicated, the large-scale distribution of nebulae brighter than magnitude 18 appears to be statistically uniform, there is a marked tendency to form clusters. The space density of nebulae is reasonably constant only if members of clusters and single field nebulae are both taken into account, so that the clusters must be considered part of the general field and not superposed on it. Clusters of several hundred members are common. This remarkable tendency has not, as yet, received very much attention theoretically.

The shape of the nearer nebulae or rather the shape of their luminous region can be studied comparatively easily. In the large majority of cases the nebula follows a spiral pattern, either of the normal or of the barred type. However, many elliptical nebulae are known as well as a relatively small number of nebulae without regular pattern.

Milne's kinematical theory closely links the shape of spiral nebulae with the theory of the universe, but this connection is not generally accepted and we shall not enter into a more detailed discussion of this theory of the shape of nebulae.

For nebulae brighter than the 18th magnitude it is possible, by an extreme refinement of technique, to observe a few absorption lines in the spectra. Detailed examination shows that, except for some of the very nearest nebulae, these lines are always shifted to the red and that the fainter the nebula the greater the shift. If the shift is interpreted as being due to a velocity of recession and the distance of the nebula is estimated by its apparent luminosity or by the luminosity of stars in it, then it appears that the velocity of recession is proportional to the distance of the nebula. Deviations from this law occur only for very near nebulae, for which the velocity corresponding to the velocity distance law is small compared with the proper motion of the nebula.

The constant ratio of velocity of recession to nebular distance is called Hubble's constant. Its numerical value is 101 miles per sec. per million light years. Its reciprocal may be expressed as a time and equals 1800 million years.

The observational raw material may therefore be summed up as follows:—

(i) The distribution of nebulae over the sky is uniform.

(ii) The distribution of nebulae in depth can be estimated by means of the luminosity distance concept. For nebulae brighter than the 18th magnitude these measurements show that the distribution is uniform with approximately one nebula per 10^{19} cubic light years. For nebulae fainter than the 18th magnitude the curve of number of nebulae per square degree against magnitude indicates a thinning out, if magnitudes are translated into distances. For our purposes the apparent magnitude itself will be most useful.

(iii) Nebulae recede from us with a velocity = distance × Hubble's constant. This law has been confirmed for nebulae brighter than magnitude 18. The reciprocal of Hubble's constant is 1800 million years.

(iv) Nebulae tend to be concentrated in clusters.

Various observations of a rather intricate nature allow deductions to be made concerning the masses of some of the nearest nebulae. The results do not agree with each other very well, but give some indication of the order of magnitude of the mass of an average nebula. Combining this with the known density of nebulae, the mean density of matter in the observed part of the universe can be worked out. The value is between 10^{-28} and 10^{-30} g./cm.^{3}. These estimates do not take account at all of non-luminous internebular material and consider only partially the effects of non-luminous interstellar material within the nebulae. Accordingly it is not impossible that the mean density of matter is appreciably higher. Various considerations indicate, however, that 10^{-25} g./cm.^{3} is almost certainly an over-estimate.

We are now in a position to review again the question put at the beginning of this section: Is the observed part of the universe likely to be a fair sample of the whole?

The answer must necessarily be speculative, but what we can say is that there is no evidence whatever to suggest that the answer should be in the negative. The large-scale uniformity of all observable characteristics throughout the observed region and the absence of any boundary effects all show that there is no reason for the rejection of the simplest hypothesis, viz. that we are observing a fair sample of the universe.

A question which is not directly observational, but closely linked with observations, concerns the effect of the red shift on the apparent magnitude of the very faintest recorded nebulae. Although the red shift is not observable for nebulae fainter than apparent magnitude 18, the velocity distance law is so accurately satisfied for brighter nebulae, that it is supposed to hold even in the region where it cannot be confirmed directly. (Observations on clusters do indicate that it continues to be valid for part of the way at least.) It is clear then that the red shifts are so large as to affect appreciably the apparent magnitude of these very faint nebulae. Furthermore, whether or not theory indicates any additional effect of the red shift on the apparent luminosity, it will evidently be affected directly by the actual shift of the spectrum. If account were taken of the entire spectrum outside the Earth's atmosphere (bolometric magnitude), then the total energy would appear to be diminished simply in the ratio of the shifted to the unshifted frequencies. Unfortunately, what is observed is not the bolometric magnitude outside the Earth's atmosphere, but the photographic magnitude at the Earth's surface. Hence the effect of the shift of the spectrum is very much more difficult to ascertain, depending as it does on the shape of the nebular spectrum and the absorption characteristics of the atmosphere. A very considerable amount of work has been done on the reduction of the data, but the uncertainty of the results is still considerable. The problem is of the utmost importance in connection with the apparent thinning out of nebulae near the limit of observation. The deviations of nebular spectra from a black-body spectrum have possibly not yet received enough attention. A very promising though very difficult technique might be the infra-red photometry of the most distant nebulae which would measure their apparent magnitudes in the part of their spectra

corresponding to the photographic parts of the spectra of nearer nebulae. This problem of the so-called K term for nebulae has by no means been finally solved.

A further, more fundamental, difficulty is that the most distant nebulae are observed at an earlier time in their career (5×10^8 years ago) than near nebulae. It is therefore by no means impossible that their intrinsic luminosity is different. This would introduce an additional error, the effect of which is entirely unknown. The comparisons between theory and observation assume constant absolute luminosity on the argument that 5×10^8 years is only a fraction of the age of a nebula.

Two rough deductions may be made immediately from the value of Hubble's constant, using purely dimensional arguments.

Some models of the universe assume a catastrophic origin of the universe, i. e. an explosion of highly concentrated matter at some event in the past, while others take a more conservative view of the origin of the universe, but whatever our model, the non-static nature of the universe associates a characteristic time with it. In Milne's theory this time is the actual age of the universe, in other models it is simply a period of relaxation. Only a most artificial theory would not give such a characteristic time a value of at least the order of magnitude of the reciprocal of Hubble's constant, and as we have said this is 1800 million years. Now, unfortunately, astrophysics, dynamical astronomy and terrestrial rocks all indicate a minimum age of the universe at least twice and possibly five times as large. This discrepancy is very real and awkward, although there are various means of explaining it.

The second point concerns the density of matter in the universe. The square of the reciprocal of Hubble's constant divided by the constant of gravitation has the dimension of a density. Again it might be argued that the actual mean density of matter in the universe should not differ very much from it. Now Hubble's constant corresponds to a density of 4×10^{-27} g./cm.^{3}, a value appreciably higher than the value observations indicate, though not necessarily incompatible with them.

Finally we must mention a fact which has been made the basis of much speculation. The ratio of the electric to the gravitational force between an electron and a proton is $2{\cdot}3 \times 10^{39}$. The reciprocal of Hubble's constant multiplied by the velocity of light (the "radius of the observable universe") is 6×10^{39} times as great as e^2/mc^2 (the classical radius of the electron.) The near coincidence of these two huge non-dimensional numbers is very striking and has been much discussed, but no generally accepted explanation has yet been given.

3. Light Signals and Kinematical Relativity

In Milne's theory the starting-point is the cosmological principle and purely kinematical considerations are used to explore the consequences of the principle. Although the cosmologies of general relativity were first found from the field equations, Robertson was able to show that one could go some way towards general relativity by the use and generalization of Milne's methods.

Before we discuss this method we must briefly consider the simplified formulation of the cosmological problem which these theories attempt to explain in the first instance. Since the universe is homogeneous only when regions containing large numbers of nebulae are considered, the large-scale structure of the universe is considered to be represented sufficiently well for the present

purposes by a uniform gas called the substratum, the molecules of which are called fundamental particles. The interaction between nebulae is very small (it is largely due to radiation) and the random motions are also small. Hence the pressure of the gas is very low and is often neglected. In Milne's formulation the cosmological principle asserts that the totality of the results of the observations, which any observer situated on a fundamental particle can make, are identical with the totality of the results of the corresponding observations any other similarly situated observer can make. Now as we have seen, the observations of nebulae which can actually be made are all due to light emitted by them and the information consists of

(i) Apparent luminosity.
(ii) Density of gas, i. e. number of nebulae per magnitude and square degree.
(iii) Red shift of the spectral lines.

The theory has to give (ii) and (iii) as functions of (i) agreeing with the functions deduced from observation.

When we try to depict nebulae and light rays graphically, it is easily seen that while (ii) and (iii) have obvious geometrical significance, it is far more difficult to see how to represent (i). The difficulty is not peculiar to cosmology, but is well known from every application of relativity and is connected with the intrinsic obscurity of the concept of spatial distance. Neither distance nor energy are invariant, and the graphical representation of the weakening of light rays along their tracks is certainly not easy.

This formidable obstacle to any attempt at developing a theory from the cosmological principle was overcome by Milne by the substitution of a new observational variable to replace (i). His definition of the permitted observations replaces an observer's measurement of the intensity of light arriving, by his measurement of the time interval between the sending of a light signal and his receipt of the reflection of the signal by the other nebulae. This ingenious artifice opened the way for a kinematical development of the theory and has since been used by Robertson to establish, on similar lines, the existence of the Riemannian metric of the general theory of relativity. However, one must not lose sight of the fact that this light-signal technique is highly artificial and bears no resemblance to actual observations. Even if a theory founded on this technique can, further on in its development, establish results concerning the intensity of light received, it must nevertheless be regarded with suspicion until the full equivalence of the two methods is established. Mathematical convenience must not be allowed to interfere with a correct representation of physical actuality, although it is frequently very useful to develop a theory on the mathematically most convenient basis, provided all its developments are always treated as provisional, pending a change of its basis from the convenient to the actual.

A second alteration Milne makes in the list of observations is that the measurement of the shift of the spectral lines is replaced by an observation of a clock on the nebula observed. With an appropriate definition of "clock", these measurements are, but for a constant of integration, equivalent, since the shift of the spectral lines measures the rate of an atomic clock on the nebula.

An assumption, which is made both in Milne's and in Robertson's work, but which is not essential, is that the world lines of all particles of the gas (Milne's fundamental observers) meet in an event in the past.

There is another point in which Milne's formulation of the cosmological principle differs to a considerable extent from astronomical actuality and which is of the greatest importance. Milne's formulation, as given above, refers to the totality of the experience of an observer, that is to say, not only to his experiences at one instant but also in the past and in the future.

We see therefore that Milne's definition of the cosmological principle and its contents deviates widely from astronomical practice: but this does not mean that it is useless. In any formulation of the cosmological principle we have to consider imaginary observers on other nebulae. Why then should this spatial generalization be allowed, while the corresponding temporal extension is forbidden? If the observers existed during the past, why should they not have emitted light as well as received it?

The use of reflection (or alternatively) the response of one observer to another's light signals is less easy to justify, but although Milne's fundamental assumptions appear to be highly artificial, they are certainly not out of place in cosmology.

The consequence of these assumptions was worked out by Milne, Walker and Whitrow and the ground was also covered by Robertson.

Walker and Robertson showed that the existence of a quadratic fundamental form specifying the propagation of light follows from these axioms and that this quadratic form is identical with that assumed in the cosmological models of general relativity. Up to this point then, the motion of fundamental particles and of light rays is identical in the two theories. Both of them have strong Newtonian elements owing to the existence of a universal time t, which is directly due to the assumption that the orbits of the particle intersect at one event in the past and nowhere else, an assumption which is a plausible extrapolation of observation.

Milne simplifies his model by demanding that the transformations from one observer to the other should be given by the Lorentz transformations. This has the effect of selecting one particular model from amongst the many possible quadratic forms, viz. the very simple one in which the flat Minkowskian 4-space of special relativity is used. As Walker has shown, this particular restriction is not part and parcel of the fundamental assumptions of the theory but merely serves to simplify it considerably.

The next step is a calculation of the orbits of other than fundamental particles, the so-called free particles. Galileo's principle is adopted and the cosmological principle then serves to yield an equation for the acceleration, containing an arbitrary function of two variables.

At this point a most far-reaching assumption is made, the so-called dimensional hypothesis. According to this hypothesis there is, in a deductive theory like kinematical relativity, no room for a fundamental length. Therefore we cannot have a non-dimensional function of a dimensional variable, since this is impossible without introducing a standard length. The universe is not merely invariant against a change of observer but also against a change of scale.

The first application of this assumption occurs in the theory of free particles, where it turns the arbitrary function of two variables mentioned above into an arbitrary function of one variable only. These equations together with the equation of continuity are applied to statistical systems of free particles. The resulting connection between density and acceleration is then interpreted as a law of gravitation. This law immediately indicates that free particles tend to cluster round the fundamental particles.

It is then shown that these new dynamical laws do not agree with Newton's laws and the discrepancy is explained as being due to the choice of coordinates originally adopted by means of the light-signal method. A logarithmic transformation leads from cosmic time t to dynamical time τ, with a corresponding transformation of space coordinates and, in these coordinates, the new dynamics has Newtonian dynamics as a first approximation.

This transformation is interpreted as meaning that dynamical processes follow a different time-scale from cosmic processes, allowing an infinite past for dynamical processes in spite of the limited "cosmic" past. This obviates most, though not all the objections raised against the short period of 1800 million years on astrophysical and dynamical grounds.

Comparing the part of the theory sketched above with observations, the extreme ease with which the velocity distance law is derived is remarkable. The identification of nebular nuclei with the fundamental particles is made by Milne. The nebulae themselves are then identified with the free particles which tend to gather round the fundamental particles. At this stage, however, very grave logical difficulties appear. As Milne himself proved, the cosmological principle implies a continuum of fundamental particles. But not only are nebular nuclei well separated, but the whole meaning of the swarm of free particles surrounding the fundamental particles becomes obscure if the fundamental particles are present everywhere.

It seems likely that the basic difficulty is the over-strict definition of homogeneity in the cosmological principle. The universe is, after all, only statistically and on the large scale, homogeneous and not absolutely homogeneous. Though no doubt it would be most difficult to build up the theory on weaker postulates, a replacement of absolute by statistical homogeneity in the cosmological principle might well make the comparison of theory and observation more convincing.

Milne and his fellow-workers have elaborated the theory so that it now covers a large part of theoretical physics. The variation of our so-called constants of nature with cosmic time is a characteristic aspect of this theory. An example of this is the variation of the "constant" of gravitation which is found to be proportional to the age of the universe. (This result is already implicit in the difference between dynamic and cosmic time mentioned above.)

Not only the fundamental assumptions but also the developments of kinematical relativity have been severely attacked. The discussion still continues, but the theory certainly deserves permanent credit for showing what a powerful tool kinematics can be and how far-reaching are the implications of a cosmological principle.

The light-signal technique was further examined by Robertson, who not only deduced the quadratic fundamental form but also examined what kinematics could say about the law of gravitation if Milne's dimensional hypothesis was not adopted. He showed that not only Milne's statistical theory but also the field equations of general relativity and a generalized Newtonian theory of gravitation can be used without inconsistency.

4. The Models of the General Theory of Relativity

The general theory of relativity bases itself on the postulate that the laws of physics are the same for any observer irrespective of his state of motion, position, or time. This postulate is an extrapolation of terrestrial experimental results

(Michelson-Morley, equivalence of inert and gravitating mass, etc.). It is further postulated that a geometry exists in which the tracks of material particles and of light rays are geodesics. This geometry, which is nothing but a representation of all dynamically possible motions, is taken to be Riemannian. The invariant interval ds is then defined in terms of any four coordinates x^μ by

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu,$$

where the ten coefficients $g_{\mu\nu}$ (the fundamental tensor) are functions of position and time. It is then found that agreement with experimental evidence requires that $ds = 0$ along a ray of light and that ds measured along the track of a particle coincides with the measurement of time by an observer travelling with the particle.

This space, which has physical significance solely by means of the physical meaning attached to ds, must be affected by the presence of matter, in order to express the gravitational effect of matter on the orbits of other bodies. The relativistic description of matter is afforded by the energy momentum tensor $T^{\mu\nu} = \rho \frac{dx^\mu}{ds} \frac{dx^\nu}{ds}$, where ρ is the invariant density and $\frac{dx^\mu}{ds}$ the velocity vector of the matter.

Now experience shows that $T^{\mu\nu}$ is conserved (conservation of mass, energy and momentum), while it can be shown from geometrical considerations that the tensor $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \lambda g_{\mu\nu}$ is also conserved (where $R_{\mu\nu}$ is a tensor constructed from the fundamental tensor and its first and second differential quotients, and R is its invariant, while λ is an arbitrary constant). Accordingly the identification is made

$$-8\pi\kappa T_{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R + \lambda g_{\mu\nu},$$

where κ is a new constant depending on the units of mass and length employed. This system of ten equations constitutes the field equations of general relativity and it is useful to consider at this stage the evidence for the validity of the field equations.

Mathematically it seems that the right-hand side is the simplest geometrical tensor satisfying a conservation law. It is known that it is not the only one, but the others are very much more complicated. The left-hand side is constructed in a straightforward way from the mass, energy and momentum of moving matter. The equation of conservation for the left-hand side is, in a Galilean local system, equivalent to Euler's hydrodynamic equation. Hence in a small region the field equations reduce to the usual equations of Newtonian dynamics.

The observational evidence for cases where the field equations deviate from Newtonian dynamics is very much poorer. The only case examined refers to an isolated spherically symmetrical singularity in empty space and the field equations are then solved for empty space only. The only solution examined corresponds therefore to zero left-hand side and the choice of the left-hand side (other than that it vanishes in empty space) has not been tested at all.

The solution for the isolated singularity is taken to describe the field near the Sun and the orbits of particles and light rays are determined. Good agreement with observation is found if λ is taken to be negligibly small. Three observations exhibit measurable differences between Newtonian and relativistic results, viz.

(i) The advance of the perihelion of Mercury. Measurement agrees with relativistic result.

(ii) Red shift of spectral lines originating on the Sun compared with terrestrial lines. Observation agrees with relativity, but the result can be derived without relativity from simple considerations of potential energy.

(iii) Deviation of rays of light grazing the Sun's limit. Relativity forecasts twice the deviation to be expected on Newtonian theory and observation tends to show that the deviation is even slightly greater than the relativistic value.

We see that mathematical evidence for the field equations is strong but not overwhelming; observational evidence exists outside cosmology for the right-hand side of the field equation only, though not for the λ term.

The λ or cosmological term has had a very chequered history. Einstein originally introduced it in the belief that thereby he might make the field equations have no solution in the absence of any masses. This was a logical requirement springing from Mach's principle according to which the distribution of masses not only determines the gravitational but also the inertial field. Hence, in the absence of any masses the field equations should not possess any solutions, i. e. there should be no $g_{\mu\nu}$, since they define the combined inertial and gravitational field.

However, de Sitter showed soon afterwards that the field equations had solutions in the absence of masses even if the λ term was included. It is a defect of the theory of relativity that so far no form of the field equations has been proposed which satisfies Einstein's original requirement of being without solutions in the absence of any masses.

While no strictly mathematical argument has been advanced against the λ term, Einstein himself has recently attacked it strongly on logical grounds, but general opinion favours its retention.

A powerful mathematical argument for the correctness of the right-hand side of the field equations is supplied by the fact that these terms imply that the motion of point masses in empty space takes place along geodesics. This argument makes no statement about $T^{\mu\nu}$ or the λ term.

The relativistic treatment of the idealized cosmological problem is founded not only upon the field equations but also on Weyl's postulate that the world lines of the nebulae form a bundle of geodesics converging towards the past, but not possessing an envelope. This postulate, which is an extrapolation from the observations of nebular motion, is of great importance.

Assuming the correctness of Weyl's postulate, it is possible to introduce a family of three-spaces orthogonal to the world lines of all nebulae. These three spaces may be taken as the coordinate hypersurfaces $t = \text{const}$. Furthermore it can be shown that the geodesic nature of the world lines of nebulae implies that if t is chosen to measure proper time for one nebula it does so for all. Hence a cosmic time t can be found measuring proper time for every nebula and defining world-wide simultaneity.

The importance of the existence of such a cosmic time was considered in Section 1. If spatial homogeneity is postulated without a stationary condition, then the introduction of cosmic time is a vital necessity; for then the cosmological principle must refer to observers at "equivalent times" and the existence of "equivalent times" implies the existence of a cosmic time.

In our case the cosmological principle states that points on a 3-space $t = \text{const}$. are physically and hence (by the postulates of general relativity) geometrically

indistinguishable. Hence these three-spaces must be spaces of uniform Riemannian curvature, but this curvature may be a function of t. On these assumptions it can be shown that a system of coordinates exists in which the metric takes the simple form

$$ds^2 = dt^2 - R^2(t)(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2)(1 + kr^2/4)^{-2}.$$

In these coordinates (r, θ, ϕ) of any particle are constant in time. $R(t)$ is an arbitrary function of t, and k an arbitrary constant which without loss of generality can be confined to the three possible values -1, 0, $+1$. (Hyperbolic, Euclidean and elliptic 3-space respectively.) This metric is identical with the metric Robertson and Walker derived from purely kinematic considerations.

The field equations can now be applied in order to show what distributions of matter and pressure are implied by this metric. Evidently both the density ρ and the pressure p will be functions of t only.* It can be proved easily that

$$\rho = -\lambda + 3\frac{k + R'^2}{R^2} \qquad p = \lambda - 2\frac{R''}{R} - \frac{k + R'^2}{R^2} \qquad R' = \frac{dR}{dt}.$$

We must now impose the physical requirement $\rho > 0$, $p \geqslant 0$. The various possible cases have been investigated in great detail by a number of authors. Since in the actual universe $\rho \gg p$ it will be sufficient to examine the case $p = 0$. The equations may then be integrated in the form

$$R^3\rho = C > 0 \qquad t = \int dR\left(\frac{3}{\lambda}R^2 - k + C/R\right)^{-\frac{1}{2}}.$$

An analysis of the different possible cases is then quite simple. If $\lambda \leqslant 0$ the universe originated from a point. Using the observational value of Hubble's constant it is seen that this catastrophic origin took place less than 1800 million years ago and accordingly this class of models cannot be reconciled with observation. For $\lambda > 0$, $k \leqslant 0$ the origin was also catastrophic, but more than 1800 million years ago. The most interesting cases arise for $k = +1$ (closed universe). Then there exists a critical value of λ called λ_e. If $\lambda > \lambda_e$ or $\lambda_e > \lambda > 0$ the development of the model is similar to those for $\lambda > 0$, $k \leqslant 0$. If, however, $\lambda = \lambda_e$ there exist three models:

(i) A static model (Einstein universe). This must be rejected because it shows no red shifts.

(ii) A model smaller than the Einstein universe, contracting from it to a point or (if we reverse the time) expanding from a catastrophic origin less than 1800 million years ago and tending asymptotically to the Einstein universe.

(iii) Lemaître's model which is expanding from a state corresponding to an Einstein universe (with which it coincided an infinite time ago). This is the only expanding model with an infinite past and has accordingly attracted most attention.

The only stationary universes are the static Einstein universe and the de Sitter universe ($k = 0$, $R \sim \exp(t\sqrt{\lambda}/3)$ which has not been included, since it is void of matter ($\rho = 0$). However, it should be noticed that all indefinitely expanding models with $\lambda > 0$ approach the de Sitter universe as $t \to \infty$ owing to the decrease of density.

* In the remaining part of this section relativistic units will be employed, i. e. time and mass will be measured as lengths (ct and $\gamma m/c^2$ resp., where c = velocity of light and γ = Newtonian constant of gravitation). In these units both p and ρ have the dimension (length)$^{-2}$.

Eddington proved that the Einstein universe was unstable. The cosmical repulsion exactly balances the gravitational attraction. If the size of an Einstein universe is increased, the increased radius increases the cosmical repulsion and the decrease in density decreases the gravitational attraction. Hence further expansion results. Similarly, contraction from an Einstein universe would continue. These developments of the Einstein universe are of course just the models described under (ii) and (iii). A considerable body of opinion holds with Eddington that the actual universe was originally in the Einstein state and the present expansion is the result of a perturbation of the Einstein universe a long time ago (10^{10} to 10^{11} years). The question of the nature of such a perturbation has attracted much attention. Eddington suggested that the formation of a condensation of matter in the Einstein universe (supposed to be homogeneous down to a molecular scale) could initiate such an expansion and the problem has been investigated by McCrea, McVittie and Lemaître. Not only has the nature of the perturbation to be investigated, but also why it led to expansion rather than contraction.

No complete solution of the problem has been found, but it seems likely that the formation of a condensation would initiate such an expansion.

So far the only observational data we have used are Hubble's constant, the fact that $\rho \gg p$ and minimum estimates of the age of the universe derived from sources other than cosmology. Is any more far-reaching comparison of theory and observation possible?

Theory can predict the relations between the apparent bolometric magnitude, the red shift and the nebular counts according to the various models, although the formulae are very awkward to deal with. The linearity of the velocity distance law down to the 18th magnitude and the nebular counts for these magnitudes set an upper limit to the curvature of space. For the faintest nebulae difficulties arise (as was discussed in Section 2), since the red shifts—though no longer measurable—give rise to a large K term. The problem then becomes very involved. The first investigations in this field were carried out by Hubble and Tolman. Their result was that the universe was closed, small and the density high.* Their values were on the verge of conflicting with evidence and they concluded that the most natural explanation of the observations was that the universe was static, the red shift being due to some unexplained cause.

This work has been very severely criticized and much fuller treatments of the question have been given by McVittie and by Heckmann. They find no evidence for Hubble's conclusions. The uncertainties of the observations are too great and, in particular, the K term too little known to permit any conclusions to be drawn concerning the sign of the curvature of space, although the curvature cannot be very large.

In concluding this section, mention must be made of the Newtonian cosmology discovered by Milne and McCrea. Attempts at such a cosmology broke down in the 19th century owing to the belief that the universe was static. An expanding (or contracting) universe is possible within the Newtonian framework. With

* Hubble's and Tolman's results were:

Present radius of the universe $= 1{\cdot}45 \times 10^8$ parsecs $= 4{\cdot}8 \times 10^8$ light years.

Mean density $= 6 \times 10^{-27}$ g./cm.^{3}.

appropriate assumption concerning the propagation of light, the Newtonian models are extremely similar to the models of general relativity with $\lambda = 0$.

5. Bibliography

Owing to shortage of space it is impossible to give here any comprehensive bibliography. H. P. Robertson's "Relativistic Cosmology" (*Rev. Mod. Phys.*, **5,** 62) and O. Heckmann's *Theorien der Kosmologie* (Springer, Berlin, 1942) give the literature before 1933 and between 1933 and 1941, respectively.

The list of some of the most important books and papers given below is necessarily very brief.

A. *Books and Reviews.*

A. S. Eddington, *The Expanding Universe*, Cambridge, 1933;
R. C. Tolman, *Relativity, Thermodynamics and Cosmology*, Oxford, 1934;
H. Mineur, *L'Univers en Expansion*, Paris, 1933;
A. Einstein, *The Meaning of Relativity*, Princeton, 1945;
E. A. Milne, *Relativity, Gravitation and World Structure*, Oxford, 1935;
M. Johnson, *Time, Knowledge and the Nebulae*, London, 1945;
G. C. McVittie, *Cosmological Theory*, London, 1937;
O. Heckmann, *Theorien der Kosmologie*, Springer, Berlin, 1942.

The first four of these books give the general relativistic point of view, the next two are devoted to kinematical relativity, while the last two give accounts of both theories.

The observer's point of view is given in the following three books:

E. Hubble, *Red Shifts in the Spectra of the Nebulae*, Oxford, 1934;
The Realm of the Nebulae, Oxford, 1936;
The Observational Approach to Cosmology, Oxford, 1937.

The cosmologies of general relativity are described fully and concisely in

H. P. Robertson, "Relativistic Cosmology", *Rev. Mod. Phys.*, **5,** 62, 1933,

while a brief modern account of the basis of kinematic relativity is given in the presidential address to the Royal Astronomical Society:

E. A. Milne, "The Nature of Universal Gravitation", *M.N.*, **104,** 120, 1944.

Both theories are briefly reviewed in

G. Temple, *Proc. Phys. Soc.*, **51,** 465, 1939;
W. H. McCrea, *Philosophy of Science*, **6,** No. 2.

B. *Papers Dealing with Specific Points Mentioned in this Article.*

R. C. Tolman, *Proc. Nat. Acad. Sci.*, Washington, **20,** 169, 1934;
W. H. McCrea, *Z. f. Astrophysik*, **18,** 98.

These two papers deal with the consequences of dropping the assumption of homogeneity.

Of papers dealing with the fundamentals of kinematic relativity we must mention in particular:

A. G. Walker, *Proc. L. M. S.* (2), **42,** 90, 1936;
M.N., **95,** 263, 1935.
G. J. Whitrow, *Proc. L. M. S.* (2), **41,** 418, 529, 1936;
Z. f. Astrophysik, **12,** 47, 1936; **13,** 113, 1937.
H. P. Robertson, *Ap. J.*, **82,** 284, 1935; **83,** 187, 257, 1936.

The important time transformation of kinematical relativity is tentatively applied to general relativity in

G. C. McVittie, *Proc. Roy. Soc. Edinburgh*, Sect. A, **62,** 147, 1945;
A. G. Walker, *Proc. Roy. Soc. Edinburgh*, Sect. A, **62,** 164, 1946.

The reasons for and consequences of putting $\lambda = 0$ in general relativity are discussed in A. Einstein's book mentioned under A and in

G. C. McVittie, *Observatory*, **62,** 192, 1939.

The problem of the effect of condensations of matter on the universe of general relativity and in particular on the unstable Einstein universe is discussed in:

A. S. Eddington, *M.N.*, **90,** 668;
W. H. McCrea and G. C. McVittie, *M.N.*, **92,** 7;
G. Lemaître, *M.N.*, **91,** 490;
G. C. McVittie, *M.N.*, **92,** 500.

The comparisons between theory and observation are mainly given in:

E. Hubble and R. C. Tolman, *Ap. J.*, **82,** 302, 1935;
E. Hubble, *Ap. J.*, **84,** 517, 1936;
G. C. McVittie, *Proc. Phys. Soc.*, **51,** 529, 1939;
W. H. McCrea, *Z. f. Astrophysik*, **9,** 290; **18,** 98.

The Newtonian expanding universe is discussed in:

W. H. McCrea and E. A. Milne, *Quart. J. Math.*, Oxford, Ser. 5, 73, 1934;
E. A. Milne, *Quart. J. Math.*, Oxford, Ser. 5, 64, 1934.

C. *Cosmological Theories Not Discussed in This Article.*

P. A. M. Dirac, *Nature*, **139,** 323, 1937;
Proc. Roy. Soc., A, London, **165,** 199, 1938;
P. Jordan, *Naturwiss*, **26,** 417, 1938.

These papers discuss a cosmology based on the variation of the "constants of nature" and particularly the constant of gravitation. The theory is closely connected with the five dimensional projective formulation of general relativity.

A new linearized theory of gravitation has been given by Birkhoff and applied to cosmology.

G. D. Birkhoff, *Proc. Nat. Acad. Sci.*, Washington, **29,** 231, 1943; **30,** 324, 1944; *Phys. Rev.* (2), **66,** 138, 1944;
C. Graef Fernandez, *Bol. Soc. Mat. Mexicana*, **2,** 43, 1945.

This theory has been criticized by H. Weyl.

H. Weyl, *Proc. Nat. Acad. Sci.*, Washington, **30,** 205, 1944;
Am. Journal of Math., **66,** 591, 1944.

A change of the relativistic field equations permitting the existence of a stationary universe is discussed in

C. Gregory, *Phys. Rev.* (2), **67,** 179, 1945.

A unification of quantum theory and general relativity with application to cosmology has been developed by Sir A. S. Eddington in a series of papers in *M.N.* and *Proc. Roy. Soc.*, London, and in two books.

E. Schrödinger has developed a generalization of relativity in a series of papers in *Proc. Roy. Irish Ac.* (since 1942).

DOUBLE STARS

New Pairs.—Jonckheere gives lists of new double stars in *J. Obs.*, **24**, 21, 69, 93, 114; **25**, 11, 25, 70; **26**, 28; **27**, 1, 5, 6, 7; **28**, 26. Rossiter's sixth list of new southern stars is given in *Publ. Michigan*, **9**, No. 2. Other lists are by Barton (*A.J.* **52**, 178), Paloque (*Annales Toulouse*, **15**, 87), Baillaud (*An. Obs. Besançon*, Nouv. Sér. 7, **3**, fasc. II) and Luyten (*Publ. Minnesota*, **3**, No. 3).

Measures.—Lists of measures are given by Baize (*J. Obs.*, **23**, 95; **24**, 127; **25**, 28; **26**, 68, 97; **27**, 29; **28**, 1, 41), by Duruy (*J. Obs.*, **23**, 145; **24**, 14; **25**, 53; **26**, 17; **27**, 50, 83, 89), by Jonckheere (*J. Obs.*, **25**, 15; **27**, 11; **29**, 49), by Fatou (*J. Obs.*, **24**, 29), by Muller (*J. Obs.*, **29**, 69), by Rougier and Sémirot (*J. Obs.*, **27**, 57), by Luplau Janssen (*Publ. Urania Obs., Copenhagen*, Ser. III, No. 1), by Eggen (*A.J.*, **53**, 21), by Hirst (*M.N.*, **106**, 154) and photographic observations by Paloque (*Annales Toulouse*, **15**, 99).

Orbits:

Double Star	*P*	*e*	*a*	Computer	Reference
ADS 671	526	0·53	12·50	Strand	*A.J.*, **52**, 107
,, 784	52·8	0·71	0·273	Eggen	*A.J.*, **52**, 111
,, 1631	293·6	0·588	1·25	Palacios	*Com. Obs. Santiago*, **1**, No. 1
,, 8987	22·35	0·520	0·209	Danjon	*J. Obs.*, **25**, 61
,, 9071	185·89	0·674	0·743	Arend	*Ann. Toulouse*, **17**, 183
,, 9494	253·60	0·297	4·008	Gennaro	*P. Padova*, No. 66
,, 11077	56·40	0·76	1·03	van Biesbroeck	*A.J.*, **53**, 23
,, 11520	12·00	0·25	0·156	Danjon	*J. Obs.*, **25**, 61
,, 14761	34·4	0·61	0·18	Eggen	*A.J.*, **52**, 208
,, 15176	48·7	0·86	0·423	Danjon	*J. Obs.*, **25**, 61
,, 16138	30	0·3	0·353	Harris	*A.J.*, **52**, 151
,, 16173	21·62	0·72	0·310	Eggen	*A.J.*, **52**, 111
,, 16314	283·7	0·515	0·492	Arend	*J. Obs.*, **27**, 22
$2^h\ 15^m{\cdot}6\ -35°$	250	0·24	1·57	Wood	*Sydney Obs. Papers*, No. 3
$16^h\ 50^m{\cdot}1\ -\ 8°$	1·71504	0·05	0·218	Voûte	*P. Riverview*, **2**, 43
$17^h\ 12^m{\cdot}1\ -34°$	42·16	0·570	1·92	Ballario	*P. Arcetri*, No. 62, 37

Miscellaneous.—Jonckheere discusses the double stars discovered by himself (*J. Obs.*, **28**, 17; *Comptes Rendus*, **214**, 153 and **220**, 680) and has notes on a micrometer for measuring faint double stars (*J. Obs.*, **26**, 53), the General Catalogues of double stars (*J. Obs.*, **27**, 73) and the double stars J 289 and J 1246 (*J. Obs.*, **28**, 58).

A method for precise measurement of the distance of a close double star is discussed by de Vaucouleurs (*Publ. Houga*, No. 12); Woolley (*Obs.*, **67**, 59) has a note on Cordoba 193; Burns (*A.J.*, **52**, 121) gives two stars of low luminosity.

Methods of orbit determination are discussed by Arend (*Annales Toulouse*, **16**, 109), van de Kamp (*A.J.*, **52**, 185 and 189) and Vidal Abascal (*Com. Obs. Santiago*, **1**, 2).

Colacevich (*Ann. Astrophys.*, **10**, 90) writes on new methods of determining dynamical parallaxes; Kozlovskaya (*A.J., Soviet U.*, **23**, 299) on the distribution of orbital inclinations of visual binaries; Baize (*B.A.*, **13**, 123) on the empirical mass-luminosity relation; Durand (*Ann. Toulouse*, **16**, 271) on ζ Herc and the

mass-luminosity relation; van de Kamp, Thomas and Keller (*A.J.*, **52**, 161 and 165) on the parallax and mass-ratio of η Cor B and 46 Taur; Abrams (*P.A.S.P.*, **59**, 78) on the spectral distribution of binary stars; Edgeworth and Hoyle (*Obs.*, **67**, 30, 58) on the formation of binary systems.

W. H. VAN DEN BOS.

SOLAR ACTIVITY

Sunspots.—Sunspots of 1947 have created a new high level in spot statistics. Exceeding the notable peaks of 1937, 1870, 1848 and 1837, the mean daily sunspot "number" (provisionally 156) for 1947 has no equivalent until the cycles are retraced to 1778, when data were less complete. But 1947 has another claim to distinction—that of producing the biggest sunspot group ever photographed and probably unique for size in all telescopic records. Furthermore, the four largest spot groups (according to peak area) of the combined epoch, 1946–47, are themselves the four largest groups in the Greenwich photographic record begun in 1874–75.

In one respect, however, the year was less distinctive. Geomagnetic storms as a whole were not commensurate with the giant spots of March and April and the numerous lesser giants during the year, that collectively provided on the average a spot visible to the naked eye on one out of every two or three days of the year. More intense magnetic disturbances may well occur within the next year or two, even though the frequency maximum of sunspots may have been reached. In May, spot frequency rose sharply, giving an average of about 17 groups per day and a mean daily sunspot number of 206·5 (Zürich provisional value), unparalleled since 1836 December when Schwabe was observing.

The life-history of the giant sunspot in south latitude 23°, near the times of its central meridian passages on February 11.5, March 10.2, April 6.8 and May 4.1, is recorded by Mount Wilson photographs reproduced in *P.A.S.P.* 1947 June, Plate X. According to preliminary Greenwich measures of area, this great group attained its peak area of 5400 millionths of the Sun's hemisphere near the time of its third meridian passage. Normally, the maximum development of a big group is reached on or about the 12th day from birth. Therefore, in the present case there must have been either (*a*) an abnormally slow rise to maturity, (*b*) unusual stability from late growth to early decay, or (*c*) regeneration of the spot formations on the invisible solar hemisphere between the first and second, and second and third transits of the disk. The final collapse of the group was sudden.

The apparent fewness of solar flares (other than minor ones) associated with this giant group has been independently commented upon in *Journal B.A.A.*, **57**, 128, 1947 and *P.A.S.P.*, **59**, 145, 1947. An intense but very short-lived flare, probably connected with this disturbed area, must have occurred on April 6 at $11^h\ 52^m$ U.T., as evidenced by the joint occurrence of a sudden fade-out on long-distance short-wave radio communication and a pronounced geomagnetic crochet impulse on the Abinger traces. An intense burst of solar "noise" was reported as having occurred from $11^h\ 58^m$ to $12^h\ 05^m$.

A solar flare that was both intense and prolonged in visible radiation, $H\alpha$, was observed at Wellington, N.Z., on July 16 between two spot groups approaching

the central meridian. A great magnetic storm began nearly 41 hours after the onset of the flare (*Observatory*, **67**, 195, 1947; where *for* "31 hours" *read* 41 hours).

The appearance of an active spot at the east limb on July 29 was at once signalized by a sequence of numerous fade-outs mainly of short duration. One of these, synchronous with a crochet on August 1 at $15^h\ 16^m$, is of special interest in connection with joint recordings of solar and cosmic noise (*Nature*, **160**, 371, 1947). The spate of solar flares must have died out after August 2, about two days before the central meridian passage of the active spot region, and no geomagnetic storm occurred.

An earlier sequence of many fade-outs occurred from May 16–30, during the abnormal peak of sunspot frequency, and is traceable by direct observation of flares to an active lune of the Sun containing four spot groups each exceeding 500 millionths of the Sun's hemisphere.

On August 23 a solar flare was observed at Sherborne at $16^h\ 55^m$ exactly *above* the east limb. This flare apparently also produced a fade-out, but no crochet was recorded at Abinger.

A spot noteworthy for its longevity (114 days or longer) was seen between 1946 December 10 and 1947 April 2 in south latitude 5° (*P.A.S.P.*, **59**, 145). Spots in 1947 appeared over a wide range of latitude, as is usual at solar maximum, but the high latitude of 46° north for a stray spot on May 5 deserves notice.

During 1947, nineteen geomagnetic storms were recorded at Abinger. Five of these were "great" storms, but since the largest range for any one of them was 510 γ in H (July 17), none was of special intensity. A bright aurora associated with the storm of April 17 is depicted in *Journal B.A.A.*, April and November. The solar activity obscurely related to this storm receives comment in *Report of the Astronomer Royal to the Board of Visitors*, 1947, p. 10. Radio echoes were observed at Manchester University from an auroral structure on the night of August 15–16 (*Nature*, **160**, 372, 1947) during one of the smaller storms.

H. W. NEWTON.

Prominences.—The mean daily areas and numbers of prominences as derived from the photographs taken at Kodaikanal on 274 days during the year are as follows:—

	Areas			*Numbers*		
	North	South	Total	North	South	Total
January–June	2·29	2·71	5·00 sq. min.	6·28	5·92	12·20
July–December	2·17	2·53	4·70 ,,	5·81	5·75	11·56

Compared with the previous year, both the areas and numbers show an increase in both the hemispheres, the increase in the northern and southern hemispheres being 9 per cent and 17 per cent for the areas and 24 per cent and 33 per cent respectively for the numbers. The latitudinal distribution of areas and numbers shows maximum activity in the zone 60°–65° in both hemispheres indicating a poleward drift of the zone of maximum in both the hemispheres. The prominence areas also show two secondary maxima between 30°–35° N. and 35°–40° S.

Twenty-nine metallic prominences were observed during the year with the prominence spectroscope, 14 in the northern and 15 in the southern hemisphere. Of these, 18 appeared at the west limb of the Sun.

Doppler displacements of the *Hα* line in prominences were observed on 148 occasions with the prominence spectroscope. In 38 cases the shifts were towards the red side, in 67 cases towards the violet side, while the rest showed displacements in both directions. The following table gives particulars of prominences which showed the largest displacements:—

Date	Coordinates of prominence	Doppler displacement observed
1947 May 13	W. Limb—16°·5 N.	6·0 A. towards red.
1947 May 16	E. Limb—22°·5 N.	6·0 A. towards red.
1947 Aug. 8	W. Limb—43° S.	6·0 A. towards violet.

Observations with the spectrohelioscope in *Hα* line showed Doppler displacements in prominences in 35 cases, 10 of which were towards the red, 11 towards the violet and the remaining in both directions.

The mean daily area of hydrogen absorption markings (without applying fore-shortening correction) computed from *Hα* spectroheliograms is 7357 millionths of the Sun's visible hemisphere, representing an increase of 50 per cent over the previous year's mean value. The latitudinal distribution shows a principal maximum in the zone 25°–30° in both the hemispheres, with secondary maxima between 55°–60° N. and 65°–75° S.

A. K. DAS.

COMETS

The year 1947 was a record one for comets, and ended with a brilliant though brief display—but only for those in the south—by the brightest comet since 1910, the year of Halley's comet and the great daylight comet 1910 I. No less than twenty-one comets were under observation during the year under review, including eight new ones but excluding one reported but not confirmed.* Three of the new ones were discovered by Michiel Johan Bester at the Boyden Station of the Harvard College Observatory, at Bloemfontein, in the course of his daily inspections of all plates after development; and Hamilton M. Jeffers at the Lick Observatory was first in detecting three of the five periodic comets whose return to perihelion had been predicted.

Observations of six of the previous year's comets were continued in 1947. Timmer's comet 1946 a was recovered by Jeffers on June 24 (19^m) and followed by him till August 9 (19^m). The periodic comets Giacobini-Zinner 1946 c and Brooks (2) 1946 e, were recorded (18^m) by him on January 24, and Tempel (2) 1946 b by G. van Biesbroeck at the Yerkes Observatory on January 15, while both Jones's comet 1946 h and Bester's 1946 k, though very faint, were still being followed at the end of 1947.

In addition to these, the two "annual" period comets, Schwassmann-Wachmann (1) and Oterma, were again recorded at around opposition. As they are being followed year by year round their orbits, they are not now included in the annual letter designations for comets. Schwassmann-Wachmann (1), = 1925 II, photographed (19^m) by Van Biesbroeck and Jeffers early in the year, was recovered by Van Biesbroeck with the 24-inch reflector ($f/4$) at the Yerkes Observatory on October 21 (18^m); and Oterma, 1943 a = 1942VII, was detected by

* *Added in press :* The numbers of discovered and observed should be increased by one, since the comet designated 1948 a was actually first found by Antonín Mrkos in 1947 on December 20 but, owing to twilight and then a spell of bad weather, was not confirmed and announced till January 18 when he himself recovered it.

Jeffers at the Lick Observatory on July 24 (18^m). The former was active again in November, being found some five magnitudes above its normal brightness, namely $12^m{\cdot}5$, on November 12 and 22 (Jeffers); but it had faded again to 18^m by December 19. Regarding its outburst in January 1946, noted in our last report, Seth B. Nicholson has drawn attention (*P.A.S.P.*, **59**, 30, 1947) to the fact that the giant spot, then present on the Sun, was on the hemisphere toward the comet at the time.

1947 a was the periodic comet Grigg-Skjellerup. It was detected on March 11.1 by H. L. Giclas with the 13-inch ($f/5$) photographic telescope at the Lowell Observatory, and independently later on the same day by E. L. Johnson with the Franklin-Adams camera at the Union Observatory at Johannesburg. It was about two degrees away from the predicted position and this probably accounts for its not having been found sooner, for it was relatively bright (11^m). It brightened to about ninth magnitude at perihelion in April, a very diffuse object of about $2\frac{1}{2}'$ diameter and only slightly condensed. Thereafter it faded rapidly, being only about fifteenth magnitude on June 25 when last photographed with certainty by Van Biesbroeck—a later record by him, on July 14, is at present unconfirmed.

1947 b, a new comet, was found first by Esteban Rondanina, an Argentinian astronomer on the staff of the Montevideo Observatory, Uruguay, on a plate of the κ Crucis region taken with the 16 cm. ($f/4{\cdot}5$) Zeiss astrographic camera on March 24.0; and independently by M. J. Bester, at the Boyden Station of the Harvard College Observatory, on a patrol plate taken with the 1·5-inch Cooke lens camera on the night of the same day. At discovery its brightness was around 9^m (estimates varied ± 2), and it brightened rapidly to 6^m early in April and reached $4\frac{1}{2}^m$ in May, when it was at perihelion, showing a bright diffuse central condensation and a slender tail several degrees long. It was seen with the naked eye in Brazil during the solar eclipse on May 20 (Van Biesbroeck). It then soon started to fade and by the latter half of June had dropped to eighth magnitude.

H. M. Jeffers, on a photograph of it taken on June 23, found two distinct tails, each $\frac{1}{4}°$ long, one sharp, narrow and straight extending westward and away from the Sun, the other broader and more diffuse, pointed south-west. At the end of June Harold L. Johnson, with the photoelectric photometer of the Lick Observatory, obtained measures of the brightness which gave magnitudes from 8·3 on June 25.4 to 10·1 on July 13. The comet was followed till September 21 when it was 18^m (Jeffers).

1947 c, a new comet, was discovered in Draco by Antonín Bečvář at the Skalnaté Pleso Observatory (Czechoslovakia), which he directs, on March 27.9, 9^m. It was found visually during a routine search for comets, which is part of the regular programme of the observatory, using one of the six 100-mm. Somet "Binar" binocular comet seekers ($\times 25$) with which the observatory is equipped, and was confirmed the same night by a photograph with the 600-mm. ($f/5{\cdot}5$) Zeiss reflector. The comet, a diffuse object about 4′ in diameter and showing but little condensation, moved rapidly northward, passed very near the Pole, and then continued southwards through Auriga and Orion and, fading, was lost in the evening twilight early in May. When last recorded, by H. L. Giclas at the Lowell Observatory on May 8, it was $11^m{\cdot}7$.

1947 d, a further discovery by M. J. Bester at the Boyden Station, was found by him on May 19 on a plate taken on May 18 with the 8-inch Bache telescope engaged on variable star work. The comet was in Lupus, within half a unit of the Earth, a diffuse object of eleventh magnitude without appreciable condensation.

In June it was described by W. H. Steavenson (30-in. refl.) as unusually diffuse in appearance, fading into the sky without any marked boundary; it was about 4′ in diameter (Merton). On June 14 he noted it as having a sensibly stellar nucleus of about fourteenth magnitude. It faded very rapidly as the distance from the Earth increased, being fifteenth magnitude in mid-July. It was last recorded with certainty on August 7, by Jeffers, $17^{m}\cdot3$, but an unconfirmed image on a plate taken by him on November 25 may also belong to it.

1947 e referred to the reported discovery of an eleventh magnitude comet on June 15 by Jakovkin Jr. at Kiev in the U.S.S.R. Numerous searches however, including that of a large plate of the area, taken by H. L. Giclas at the Lowell Observatory about the time of the supposed discovery, failed to disclose any new object.

1947 f was the periodic comet Faye, which was detected by Jeffers, near the predicted place, as a small nearly stellar coma of about seventeenth magnitude on a plate taken with the 20-inch astrograph at the Lick Observatory on June 19.4. On a photograph of it on July 25, when it was about $14^{m}\cdot5$ with coma 10″ in diameter, he found a narrow tail 4′ long. The comet reached its greatest brightness in November, after perihelion (Sept. 28). It was then about $12^{m}\cdot5$, a circular diffuse object about $\frac{3}{4}'$ in diameter with a central condensation of about 5″ (Steavenson). It was still under observation after the end of the year.

1947 g, the periodic comet Whipple, was also found by H. M. Jeffers at the Lick Observatory, on a plate taken with the 36-inch Crossley reflector ($f/5\cdot8$) on June 21.4, 18^{m}; and independently by Van Biesbroeck with the 24-inch reflector ($f/4$) at the Yerkes Observatory on June 26, a small fuzzy spot on the plates, about 17^{m} or 18^{m}, in the position predicted. The comet will not reach perihelion till 1948 June 25.7 but its orbit, lying between those of Mars and Jupiter, is of such moderate eccentricity (0·36) that it is within reach of observation at opposition for some time before and after perihelion. In fact, L. E. Cunningham has suggested it may be possible to record it at opposition each year.

1947 h, a new comet, was discovered by Carl A. Wirtanen at the Lick Observatory, as a trail on a plate taken for the special proper motion programme with the Carnegie 20-inch ($f/7\cdot4$) astrographic camera on July 18.4, a small diffuse object in Aquarius of magnitude $12\frac{1}{2}$ with an almost stellar condensation and a tail 3′ in length. W. H. Steavenson, observing it on August 6 at Cambridge, with his 30-inch reflector ($\times 150$), described it as one of the smallest comets he had ever seen : diameter 10″ with a central condensation of 3″. It was at perihelion when discovered and faded with unexpected rapidity, being recorded by Jeffers on November 7 as only $17^{m}\cdot5$, about two magnitudes fainter than had been anticipated.

1947 i, the periodic comet Encke, was detected near its predicted position by H. M. Jeffers at the Lick Observatory, on a plate taken with the Crossley reflector on August 14.4. He described it as diffuse and very faint, with a fan-shaped and not quite stellar coma of the eighteenth magnitude. It brightened slowly at first, Van Biesbroeck reporting it as fifteenth magnitude in mid-September, and then more rapidly, reaching eighth magnitude in mid-October, when it showed a fan-shaped coma, about 4′ across, moderately condensed and with a well-defined nucleus, the coma extending some 7′ *towards* the Sun. It was then on the average $1^{m}\cdot3$ brighter than predicted by Van Biesbroeck's formula (*A.J.*, **36**, 43, 1924) but came into accord with it at the beginning of November. When last seen in the morning twilight, at the Tokyo Observatory on November 22.9, three days

before perihelion passage, it had reached $5^m.5$. A study of the visual estimates of brightness has been undertaken at the Warsaw Observatory and Dr J. Gadomski has requested observations to be sent to him. He has remarked that the development in appearance was different from other comets : at the start a diffuse spot, then it condensed gradually, and later became star-shaped (M. Mazur).

1947 j, a new comet, was discovered in Pegasus by Karl Reinmuth on two routine minor planet plates taken with the 40-cm. Bruce photographic telescope at the Königstuhl Observatory at Heidelberg on September 10–11 : a small diffuse object, $12^m.7$, with a fourteenth magnitude nucleus. Its orbit was found to be one of short period, Reinmuth's second discovery of this nature. It had passed perihelion when discovered and was fading, but it was followed into the next year.

Tracing the path back it was found that the comet's motion must have experienced heavy perturbations between the middle of 1943 and the end of 1945, while it was within about one astronomical unit of Jupiter, and the suggestion was made that it might be identical with Tuttle (1858 III)–Giacobini (1907 III). However, the result of a preliminary investigation, by E. Rabe at Heidelberg, has shown this to be impossible. Rabe has undertaken the definitive investigation of the orbit.

1947 k, another new comet, was discovered by M. J. Bester at the Boyden Station at Bloemfontein, on a plate taken for the routine patrol with the 3-inch Ross lens camera, on September 24–25. It was in Eridanus, a small, diffuse, centrally condensed object of the eleventh magnitude. It brightened to 9^m by November and showed a twelfth magnitude nucleus and a faint tail some minutes of arc long. By the end of the year it had reached the eighth magnitude and a photograph taken at the Boyden Station showed a tail 3° long. It was followed into the next year, still increasing in brightness as it approached perihelion in 1948 February.

1947 l, the periodic comet Schwassmann-Wachmann (2), originally discovered in 1929, was detected on this its third observed return by Van Biesbroeck, on a plate taken with the 24-inch reflector at the Yerkes Observatory on October 20.2, in the position predicted by H. Q. Rasmusen. It showed a round diffuse coma, 12″ in diameter, 16^m. Like Whipple's, this comet has a moderate eccentricity (0·38) which keeps it within range of observation for some time before and after perihelion passage—at this return, 1948 August.

1947 m, another new comet, as the result of systematic searching with a 15 inch-reflector (× 23), was discovered in Corvus by Minoru Honda, an amateur astronomer at Kurashiki (Okayama Prefecture) in Japan on November 13.8, just prior to its perihelion passage. It was a slightly condensed diffuse object of the eighth or ninth magnitude. Its motion carried it rapidly into high south declination, so that it could not be followed by northern observatories. By December 19, when Johnson last recorded it with certainty at the Union Observatory, Johannesburg, it had faded to the tenth magnitude, and an unsuccessful search by Albert Jones (8-inch reflector, × 36) early in the following January indicated it was then fainter than the twelfth magnitude.

1947 n, the last comet of the year, appeared unexpectedly, a fine spectacle in the evening skies of the southern hemisphere, on December 8. The first news of it came from the Cape but numerous reports from places on land, and from ships at sea, followed, two of these claiming to have seen the comet the previous night, December 7. Its brightness on December 8 appears to have been about -1^m; by December 13 it had faded to 3^m. The head was described as of an orange colour

and a tail stretched vertically upwards in the sky for 20° to 30° curving towards the south; in appearance it was very like Comet 1910 I.

Accurate observations of position proved difficult to obtain in the twilight but Jorge Bobone, on December 10·0, at the Cordoba Observatory in the Argentine, was successful in obtaining the first. Later, on the same day, Van den Bos, at the Union Observatory in Johannesburg, was able to observe the comet telescopically and immediately detected that the nucleus was double, the components being 6″ apart. He obtained a series of measures covering almost every night to the 20th when bad weather intervened, but by then observations of the components were being obtained at observatories in the U.S.A. There was a gradual increase in the separation (to 21″ on January 10) and change in position angle, but the remarkable feature was the variation of the relative brightness of the components : the one which was the fainter by four magnitudes on December 10 was slightly the brighter on the 15th and 16th, then faded again relative to the other. On December 16 and 17 long exposure photographs were obtained, at the Boyden Station at Bloemfontein, which showed two tails 20° long and no less than three others shorter and fainter.

Table of the Elements

Comet		*T* (U.T.)	*q*	*e*
1930 IV	Beyer	1930 Apr. 18·1212	2·078673	1·000379
1946 b	P/Tempel (2)	1946 July 2·3436	1·393315	0·542233
1947 a	P/Grigg-Skjellerup	1947 Apr. 20·435*p*	0·853190	0·704486
		1947 Apr. 18·1370	0·853130	0·704259
1947 c	Bečvár	1947 May 3·9198	0·961836	1·0
1947 b	Rondanina-Bester	1947 May 20·9669	0·559816	0·997503
1947 d	Bester	1947 May 31·1155	1·402874	1·0
1947 h	Wirtanen	1947 July 18·937	2·8283	1·0
1947 j	P/Reinmuth (2)	1947 Aug. 18·5789	1·863161	0·469017
		1947 Aug. 19·5650	1·866728	0·468958
1947 f	P/Faye	1947 Sept. 28·4001	1·663269	0·563602
1947 m	Honda	1947 Nov. 12·013	0·7177	1·0
		1947 Nov. 19·445	0·7435	1·0
1947 i	P/Encke	1947 Nov. 26·591*p*	0·340337	0·846566
		1947 Nov. 26·3295	0·341130	0·846197
1947 n	Southern Comet	1947 Dec. 2·5811	0·109857	1·0
		1947 Dec. 2·5869	0·110050	1·0
1947 k	Bester	1948 Feb. 16·4330	0·747809	1·0
1947 g	P/Whipple	1948 June 25·846*p*	2·448768	0·355630
1947 l	P/Schw.-Wach. (2)	1948 Aug. 24·242*p*	2·15241	0·38370
		1948 Aug. 23·632*p*	2·152282	0·383830

References and Notes to Table of Elements

1930 IV Beyer. (1) G. Pels, *B.A.N.*, **10**, 237, 1947. Definitive, from 249 observations covering 673^{d}. Osc. epoch 1930 September 24.

1946 b P/Tempel (2). (2) L. E. Cunningham, *HAC*, No. 842. From observations covering 210^{d}, with first-order Jupiter perturbations taken into account. Osc. epoch 1946 June 29·0.

1947 a P/Grigg-Skjellerup. (3) F. R. Cripps, *B.A.A. Handbook*, 1947. Prediction based on his elements in *Handbook*, 1942. (4) L. E. Cunningham, *HAC*, No. 821. From observations covering 49^{d}, assuming corrected period deduced from Cripps's prediction, namely $P=4{\cdot}899533$.

From December 15 to 23 the McDonald Observatory was able to obtain spectrograms which included records of the infra-red region. On these were found a band with a sharp maximum at $\lambda 7908$ A., and probably a secondary maximum at 7869 A., which it was suggested were due to a rotation-vibration band of ammonia but which were later identified as belonging to the Cyanogen red system.

This was not a great comet. Although for a day or two its brightness was seen to exceed that of any other comet since 1910—the effect of its small perihelion distance (0·11)—it faded very rapidly and by the end of the month was no brighter than eighth magnitude. Early in 1948 January the Sun started to gain on the comet in the evening sky, the last known observation being that by Van Biesbroeck on January 20 ($10^{m}\cdot5$), after which the comet was lost in the evening twilight.

The table of the elements of cometary orbits which follows is arranged as in the last report : the comets are listed in order of perihelion date ; the symbol P/ indicates a periodic comet, and *p* after the perihelion date that the elements were predicted ones.

of Cometary Orbits

Period (years)	ω	Ω	i	Equinox	Computer	Ref.	Comet
	°	°	°				
...	24·6213	116·3925	71·9751	1930·0	Pels	1	1930 IV
5·31	190·8549	119·4163	12·4310	1950·0	Cunningham	2	1946 b
4·91	356·3915	215·3712	17·6466	1950·0	Cripps	3	1947 a
4·90	356·4011	215·3747	17·6456	1950·0	Cunningham	4	1947 a
...	182·1407	322·3300	129·1579	1947·0	Cunningham	5	1947 c
3356	303·7646	353·1630	39·2913	1947·0	Cunningham	6	1947 b
...	357·3973	232·3245	111·4117	1947·0	Cunningham	7	1947 d
...	9·55	311·07	97·37	1947·0	Cunningham	8	1947 h
6·57	43·3434	297·4469	7·1262	1947·0	Rabe	9	1947 j
6·59	43·9653	297·3611	7·1257	1950·0	Cunningham	10	1947 j
7·44	200·5230	206·3072	10·5333	1947·0	Cunningham	11	1947 f
...	205·27	295·97	95·63	1947·0	Cunningham	12	1947 m
...	225·67	314·57	111·42	1947·0	Hirose	13	1947 m
3·30	185·1991	334·6798	12·3501	1947·0	Matkiewicz	14	1947 i
3·30	185·1985	334·7223	12·3505	1950·0	Merton	15	1947 i
...	196·1953	336·6422	138·4339	1950·0	Schmitt	16	1947 n
...	196·2018	336·5654	138·5071	1947·0	Hirst	17	1947 n
...	350·2410	270·6914	140·5633	1947·0	Cunningham	18	1947 k
7·41	190·1196	188·5963	10·2468	1950·0	Dinwoodie	19	1947 g
6·53	358·1204	126·0229	3·7237	1950·0	Beart, Henderson	20	1947 l
6·53	358·1213	126·0213	3·7236	1950·0	Rasmusen	21	1947 l

1947 c Bečvář. (5) L. E. Cunningham, *HAC*, No. 807. From observations covering 14^{d}. The angular elements were deduced from his constants.

1947 b Rondanina-Bester. (6) L. E. Cunningham, *HAC*, No. 857. From observations covering 146^{d}. Two observations 32 days later showed a residual of $4\frac{1}{2}''$ only. He states that a parabolic orbit would leave a residual (elsewhere) of about $0°\cdot1$.

1947 d Bester. (7) L. E. Cunningham, *HAC*, No. 838. From observations covering 49^{d}.

1947 h Wirtanen. (8) L. E. Cunningham, *HAC*, No. 839. From observations covering 6^{d}.

1947 j P/Reinmuth (2). (9) E. Rabe, *N.A.Z. Vorl. Mitt.*, No. 19 and *UAIC*, No. 1114. From observations covering 27^{d}. Rabe has undertaken the definitive investigation of the orbit. (10) L. E. Cunningham, *HAC*, No. 888. From observations covering 96^{d}.

1947 f P/Faye. (11) L. E. Cunningham, *HAC*, No. 853. From observations covering 65^d, assuming $a=3{\cdot}8113557$.

1947 m Honda. (12) L. E. Cunningham, *HAC*, No. 862. Cabled observations discordant; elements uncertain. (13) H. Hirose, *UAIC*, No. 1122. From rough observations.

1947 i P/Encke. (14) L. Matkiewicz, *UAIC*, Nos. 1090, 1106. Predicted elements (converted to ecliptic) which, after altering T to 1947 November 26·318 U.T. to obtain best fit for observations of August 14·4 and October 26·1, left residuals of about 5′, apparently mainly due to error in the value of the eccentricity. (15) G. Merton, MS. Preliminary correction of Matkiewicz's orbit, which reduced these residuals to a few seconds of arc. Corrected value of period=3·303196 assumed; elements ω, Ω and i unchanged but given for equinox 1950·0.

1947 n, the Southern Comet. (16) A. Schmitt, *UAIC*, No. 1139. From 9 observations at Algiers covering 22^d. (17) W. P. Hirst, *UAIC*, No. 1144. From 18 observations covering 25^d.

1947 k Bester. (18) L. E. Cunningham, *HAC*, No. 855. From observations covering $9\frac{1}{2}^d$ —an unusually successful preliminary determination.

1947 g P/Whipple. (19) Cameron Dinwoodie, *B.A.A. Handbook*, 1948. Prediction based on the elements by D. H. Sadler and Miss F. M. McBain for 1940 quoted in last report (*M.N.*, **107**, 110 ; ref. No. 33). The recovery observation of 1947 June 21 indicated T 1948 June 25·770.

1947 l P/Schwassmann-Wachmann (2). (20) W. E. Beart and W. P. Henderson, *B.A.A. Handbook*, 1948. Prediction based on the elements by W. P. Henderson and H. Whichello in *Handbook*, 1941. (21) H. Q. Rasmusen, MS. Based on his previous investigation of the orbit, *Pub. Copenhagen Obs.*, No. 106, 1935. The recovery observation of 1947 October 20 indicated T 1948 August 23·5.

Additional Notes

1941 VI P/Schwassmann-Wachmann (1)=1925 II. An investigation of the orbit 1934–44, by Paul Herget, has been published in *A.J.*, **53** (No. 1165), 16, and predicted ephemerides to 1951 July are given. His basic osculating elements, for 1941 January, were included in our last report (*M.N.*, **107**, 110 ; ref. No. 35).

1942 VII P/Oterma=1943 a. An investigation of the orbit 1943–44, also by Paul Herget, has been published in *A.J.*, **53** (No. 1165), 18, and predicted ephemerides to 1951 August are given. His basic osculating elements, for 1943 October, were included in our last report (*M.N.*, **107**, 110 ; ref. No. 41). Herget remarks that as there was a very close approach of the comet at aphelion to Jupiter at perihelion in 1937, and another will take place in 1961, many well-spaced accurate observations (not only at opposition) must be obtained during the next few years to determine the orbit with sufficient exactitude for the investigation of the very large alterations to the orbit during these approaches.

Corrigendum

107, 111 ; note on 1910 III Metcalf, at foot of page, line 5. For " Yamarnato " read " Yamamoto ".

G. MERTON.

ADDRESS

Delivered by the President, Professor W. M. H. Greaves, on The Photometry of the Continuous Spectrum

After some hesitation I have selected "The Photometry of the Continuous Spectrum" as the topic of to-day's address. My hesitation is due to the difficulty of presenting an adequate survey in the time available, but I have been encouraged to make the attempt by the consideration that the subject can be used to illustrate the way in which Natural Knowledge is advanced by an interplay between observational and theoretical investigations. But before I can come to this aspect of the developments which have taken place, I think that many Fellows would probably welcome a general description, not too detailed, of the kind of measurement which is undertaken in this comparatively new technique, and of the relation of the technique to that of classical photometry. I propose to begin by trying to give such a survey.

The photometry of the continuous spectrum is one of the two main subdivisions of spectrophotometry, a subject which bears very much the same relationship to the older spectroscopy as the classical heterochromatic stellar photometry does to positional astronomy. Apart from purely descriptive work, the importance of which should not be forgotten, a telescope can be used either for the measurement of the positions of heavenly bodies or for the measurement of their brightnesses; similarly a spectroscope, apart from descriptive surveys such as the estimation of spectral types, can be employed for the measurement of wave-lengths of spectral lines or for the measurement of the light received from a star within definite wave-length ranges. If such measurements of the light received are to refer to the continuous spectrum alone, no contributions to the measures being made by wave-lengths affected by spectral lines, it is necessary to isolate quite small spectral ranges, and the measures are then measures of monochromatic brightness, or of monochromatic magnitude; they are, to some extent, analogous to the older measures of heterochromatic magnitude, but they possess certain distinctive properties. It will be instructive, I think, to devote a little time to a comparison of the principles involved in monochromatic and heterochromatic measurement.

Let us take heterochromatic magnitudes first. I suppose that many a first-year student in our Universities feels that he knows what he means by the magnitude of a star. He has been told that the difference of magnitude between two stars is two and a half times the common logarithm of the inverse ratio of their brightnesses, and there it is! It is not until later that he realizes that the whole question has been begged by the introduction of the word "brightness", and that this word represents a somewhat complicated conception. It does not represent the total radiant energy received from a star, since all wave-lengths do not affect the apparatus used, and, indeed, some wave-lengths are inaccessible to observation. Neither does it represent the total energy received over a definite wave-length range, since the sensitivity of the receiving apparatus (which may be the eye, or a photographic plate, or a physical receiver such as a photoelectric cell) varies with wave-length throughout the spectral range to which it is sensitive.

In the simplest case, when the Purkinje effect or any analogous phenomenon is not introducing a complication, the sensitivity factors depend on the wave-length only and the brightness can then be defined as the integral, with respect to wave-length, of the energy received per angstrom multiplied by the sensitivity factor. Brightness is thus not a very simple physical quantity, and only becomes such when the range of wave-length involved is very small. We then have the case of monochromatic photometry for which brightness *is* capable of being defined as a simple physical quantity. The monochromatic brightness at any wave-length can, in fact, be defined as the energy received per angstrom at that wave-length, and the difference of monochromatic magnitude between two stars can then be defined, in the ordinary way, as being 2·5 times the common logarithm of the inverse ratio of their monochromatic brightnesses. In the measurement of monochromatic magnitudes we have then to isolate a small range of wave-length for measurement, and, if the measures are to refer solely to the continuous spectrum, this small range must be unaffected by absorption or emission lines. For wave-lengths which are so affected we can infer what the measures would have been if the lines had been absent by interpolation between measures at neighbouring wave-lengths, and in this way we can, for any assigned wave-length, develop a system of monochromatic magnitudes, appertaining to the continuous spectrum, which are analogous to the older heterochromatic magnitudes, but which are capable of being defined in simple physical terms. They also possess another distinctive property; for a given absorbing medium, such as a block of glass or the atmosphere at the zenith on a particular occasion, the absorption expressed in monochromatic magnitudes is directly proportional to the mass-thickness of the absorbing material, the constant of proportionality being dependent on the nature of the material and the wave-length employed. This is not so in heterochromatic photometry where (apart from the simple case in which the absorption coefficient does not vary with wave-length) the absorption in magnitudes of a block of material depends on the distribution with wave-length of the incident light throughout the spectral range to which the receiving apparatus is sensitive. Thus, in ordinary visual or photographic photometry the absorption of the atmosphere at the zenith on a particular occasion, expressed in magnitudes, depends on the colour of the star which is being observed, whereas for any monochromatic system the atmospheric absorption on a particular occasion is, for all stars, a perfectly definite quantity which can be derived from measures performed on stars at different zenith distances; and if this be done then the measured difference of monochromatic magnitude between a star and a terrestrial source of light can be corrected for atmospheric absorption. An analogous operation cannot be accurately performed in heterochromatic photometry, since, for a given star, the colour is altered progressively as the beam passes through the atmospheric layers, and so the absorption in magnitudes is no longer proportional to the air mass traversed.

It is not my purpose to-day to describe in detail the technique of monochromatic spectrophotometry. The principle is simple: the receiving apparatus, usually a photographic plate in the focal plane of the camera lens of a spectrograph, has to be calibrated by exposure to light sources for which the magnitude differences have been determined by laboratory methods (some form of variable aperture method is often used). This calibration process provides the means for converting measures of photographic density, or other equivalent measures

of instrumental response, to monochromatic brightnesses, and magnitude differences can then be deduced. I ought to add that although the principle is simple there are some difficulties in the application, but I cannot discuss the details to-day. We may assume for the present purpose that the difficulties have been met, and that for every wave-length concerned a system of monochromatic magnitudes appertaining to the continuous spectrum has been developed. It would then remain to fix the zero point for each system just as in the case of the classical visual and photographic magnitude scales. This could be done by assigning some definite magnitude for each wave-length to the mean of a selected group of stars, and it would be natural, and would be a logical extension of the way in which the zero point for photographic magnitudes has been defined in the past, to make, by definition, the monochromatic magnitude equal to the visual at all wave-lengths for a selected group of stars of spectral type Ao. But no generally accepted system of zero points has yet been adopted, for a reason to which I shall refer presently.

The next natural step would be to difference systems of monochromatic magnitude, thereby obtaining quantities analogous to heterochromatic colour indices. It has been found convenient to define quantities called relative spectrophotometric gradients by differencing two systems of monochromatic magnitude, obtained at contiguous wave-lengths, and dividing these differences by the difference of the reciprocals of the two wave-lengths concerned. The relative gradients are then obtained by multiplying the resulting quotients by the number $\frac{2}{5}\log_e 10 = 0{\cdot}921$, so that the difference of gradient between two stars is

$$G_{2\lambda} - G_{1\lambda} = \frac{d}{d(1/\lambda)} \log_e \frac{B_{1\lambda}}{B_{2\lambda}} = 0{\cdot}921 \frac{d}{d(1/\lambda)}(m_{2\lambda} - m_{1\lambda}),$$

where G denotes gradient, B monochromatic brightness, m monochromatic magnitude and λ wave-length (in microns). The definition of relative gradient is thus:—

$$G_\lambda = 0{\cdot}921 \frac{dm_\lambda}{d(1/\lambda)}.$$

The relative gradient of a star is then a function of wave-length. But the convenience of relative gradients is due to the circumstance that for normal stars (i. e. excluding reddened stars to which I shall have to refer later) the variation of relative gradient with wave-length is actually small over considerable wave-length ranges, the difference of monochromatic magnitude between two stars varying approximately linearly with the reciprocal of the wave-length. Such an approximate linear relationship is characteristic of black-bodies, but I had better state at this point that the converse does not apply, and that although the relationship is observed to hold good approximately for stars over considerable wave-length ranges, this does not imply that stars radiate as black-bodies. In fact we shall see presently that such an inference could not even be regarded as being roughly true. But for the present we are only concerned with the empirical fact that the variation of relative gradient with wave-length is normally small over considerable ranges. A practical consequence of this is that in measuring gradients we can difference monochromatic magnitudes for wave-lengths which are fairly widely separated, the relative gradient being then obtained by dividing

the magnitude difference by the difference of the reciprocals of the two wave-lengths and multiplying the quotient by 0·921. The gradient so derived can be regarded as appertaining to the harmonic mean of the two wave-lengths. Since relative gradients are thus obtained by differencing systems of monochromatic magnitude they are analogous to heterochromatic colour indices, but it should be observed that gradients appertain to the continuous spectrum only, whereas colour indices, since they are obtained by differencing the magnitudes in two heterochromatic systems, naturally involve contributions to the total brightnesses made by the absorption or emission lines in the spectral ranges considered. For this reason it is not surprising to find, as Atkinson, Hunter and Martin (**1**) have found, that there is no very definite relationship between gradients and colour indices. To derive gradients from colour indices it would be necessary to apply to the magnitudes involved in the latter corrections for the effect of the lines, and the determination of such corrections involves another spectrophotometric operation, the measurement of line intensities. As an example of the kind of corrections involved, E. G. Williams (**2**) found that the corrections to a set of photoelectric magnitudes obtained by Elvey with a violet filter ranged up to $0^{m}\cdot44$ and that those to the photoelectric magnitudes obtained by Stebbins and Huffer with a blue filter ranged up to $0^{m}\cdot23$. Both of these sets of magnitudes were heavily affected by the higher members of the Balmer series of hydrogen lines.

Up to now we have been considering differences of gradient between actual stars, the procedure being analogous to the older technique of obtaining colour indices. But we can take a further step which, as has been indicated previously, is not possible in the case of heterochromatic magnitudes and colour indices; we can measure the differences of monochromatic magnitude, and so the difference of gradient, between a star and an artificial star incorporating a terrestrial source of light, and we can correct the measures so obtained for the absorbing effect of the Earth's atmosphere, the atmospheric corrections being derived from measures on stars observed at varying zenith distances. If the relative spectral energy distribution of the terrestrial light source has been obtained by standardization in the laboratory, the measures of gradient difference between star and artificial star give us the relative spectral energy distribution of the star. The results are conveniently expressed in the form of what are known as absolute gradients, the absolute gradient ϕ_λ of a star at wave-length λ being defined by the formula

$$\phi_\lambda = -\frac{d}{d(1/\lambda)} \log_e(\lambda^5 I_\lambda),$$

where $I_\lambda d\lambda$ is the energy emitted by the star between wave-lengths λ and $\lambda + d\lambda$, i. e. I_λ represents the energy radiated per angstrom at wave-length λ. It is easy to see that the difference of gradient, as previously defined, between two stars, or between a star and an artificial star, is equal to the difference of the quantities ϕ_λ, and since for an artificial star ϕ_λ is calculable from the relative spectral energy distribution, which is given by the standardization, the measures give, for any wave-length λ concerned, the value of ϕ_λ for any star which is measured against an artificial star.

For a black-body radiator a measure of the absolute gradient ϕ_λ would at once give the temperature of the radiator. It easily follows from Planck's

formula that for a black-body

$$\phi_\lambda = \frac{c_2}{T} \Big/ (1 - e^{-c_2/\lambda T}),$$

where T is the temperature and c_2 is a physical constant whose numerical value is 14,320 microns. degrees. We can measure ϕ_λ at various wave-lengths and for a black-body radiator the resulting values of T calculated by using this last equation will, of course, be all the same. But when we measure ϕ_λ for a star at various wave-lengths, and calculate the temperature in this way, we find that the values of T obtained for the different wave-lengths are not all the same; this is because the stars are not radiating as black-bodies, and the "temperatures" we thus obtain for stars are called *colour temperatures*, the colour temperature of a star at any particular wave-length being the temperature of a black-body for which the value of ϕ_λ is the same as for the star. (This is equivalent to defining the colour temperature as the temperature of a black-body radiator for which $\frac{d}{d\lambda} \log_e I_\lambda$ is the same as for the star.) The observational results for stars are often expressed in the form of colour temperatures, which are simply calculated from the measured quantities ϕ_λ, but it is perhaps necessary to give a warning that this practice can be very misleading if it creates the impression that the values obtained represent the actual physical temperatures in the reversing layers of stars. They most certainly do not. For example, the colour temperature of a normal star of spectral type A0 is about 16,000 deg. absolute at wave-length 5000 A., whereas the average temperature of the reversing layer is believed to be about 10,000 deg. The colour temperatures of a star at the various wave-lengths are merely species of code numbers expressing the way in which the radiation emitted is distributed with wave-length, and provided that is properly understood there is no harm in expressing the results of our measures in this way, but it is probably better to give values of ϕ_λ rather than values of the colour temperature, since it is the quantities ϕ_λ which come naturally out of the measures.

Before leaving this brief description of the measurement of gradients, which omits all technical experimental details, there is one further remark I ought to make. We have seen that gradients are measured by differencing monochromatic magnitudes obtained at different wave-lengths. Clearly any error in the magnitudes which does not vary with wave-length does not affect the gradients, since such errors cancel out in the differencing. One such source of error would be inequality in spectrum breadth as between star and star. Up to now no special precautions have, as a rule, been taken against errors of this type, with the result that we now have available relative gradients of a high order of accuracy but not correspondingly accurate monochromatic magnitudes. It is for this reason that no attempt has been made to get an agreed definition for the zero points of the latter. Observers have been content to define the zero point of relative gradients by assigning zero gradient to the mean of a selected set of stars, and to leave it at that. It is possible that more attention will be given to monochromatic magnitudes in the future.

In addition to measuring absolute gradients, and thence deriving colour temperatures, spectrophotometric comparisons between stars and standardized laboratory light sources allow us to measure any discontinuities which may exist in the continuous spectrum. Such a discontinuity exists at about λ 3700

near the series limit of the Balmer series of hydrogen lines, the light emitted per angstrom on the long wave-length side of the discontinuity being usually greater than the light emitted per angstrom on the short wave-length side. Measures of the Balmer discontinuity have been made at Jungfraujoch by Barbier, Chalonge and their collaborators (**3**), and they have expressed their measures in the form

$$D = \log_{10}(I_{\lambda+}/I_{\lambda-}),$$

where $I_{\lambda+}$ and $I_{\lambda-}$ denote the emitted energies per angstrom at wave-lengths immediately greater than and less than the wave-length λ of the discontinuity. The values of D vary with spectral type; for main sequence stars the discontinuity reaches its maximum value at spectral type A0 for which type we have $D = 0{\cdot}47$, so that the intensity of the continuous spectrum on the long wave-length side of the Balmer discontinuity is about three times the intensity on the short wave-length side, the break in the continuous spectrum being thus large for main sequence A0 stars. For super-giants of the same spectral type the discontinuity is less, and it seems to reach its maximum value for super-giants at about type F0. For normal stars of type B0 the value of the discontinuity is $D = 0{\cdot}04$, the corresponding intensity ratio being only 1·1 to 1.

There is another quantity appertaining to the continuous spectrum which can be measured in the case of a limited number of stars. This is the radiation per angstrom per square centimetre of surface at any wave-length, and it can be expressed in the form of what is known as the *brightness temperature*, this being defined, for any given wave-length, as the temperature of a black-body radiator for which the radiation per angstrom per square centimetre of surface is the same as the corresponding quantity for the star. But unlike colour temperatures, which can be measured for all stars, brightness temperatures can only be measured for stars whose angular diameters are known. If the brightness temperature at any given wave-length be measured for the Sun, then it can be obtained, for the same wave-length, for any star of known angular diameter, provided the difference of monochromatic magnitude at that wave-length between the Sun and the star be measured. This measurement is more easily said than done, and at present the only brightness temperatures, in the strict sense, which are available are for the Sun itself. But approximations to brightness temperatures at λ 5300 can be got for stars of known angular diameter by regarding visual magnitudes as monochromatic magnitudes at this wave-length, and in this way, using the data for eclipsing binaries of known parallax, a scale of brightness temperatures for λ 5300 has been indicated—in view of the nature of the material I don't think one can put it stronger than that—ranging from 28,000 deg. at type O8 through 18,000 deg. for B0 to about 11,000 deg. for A0 and about 9000 deg. for F0.* It must be emphasized that, like the colour temperature, the brightness temperature of a star is really a kind of code number expressing the results of certain measures of the energy radiated; care has to be exercised in interpreting it in terms of the physical temperature of the surface.

For a black-body radiator the colour and brightness temperatures would be the same at all wave-lengths, each being equal to the physical temperature of

* These are the values given by Gaposchkin (*A.N.*, **248**, 214, 1933). They are obtained by utilizing visual magnitudes and applying a correction from visual to bolometric based on the assumption of black-body radiation. This means that they are really brightness temperatures for the effective wave-length of visual light.

the radiator. But for a star we must expect the brightness temperature, like the colour temperature, to vary with wave-length. As an example of the relation between brightness temperature and colour temperature *, I will quote some figures for the Sun derived from Pettit's measures (**4**). At λ 4500, λ 5500 and λ 6500 the brightness temperatures of the integrated disk are about 6200 deg., 6100 deg. and 6000 deg., respectively, the brightness temperature varying by about 100 deg. per 1000 A. in this region of the spectrum. The corresponding colour temperatures at λ 5000 and λ 6000 are 6720 deg. and 6790 deg. respectively. For the centre of the disk the values for colour and brightness temperatures are about 200 deg. higher than these values. For wave-lengths shorter than λ 4500 the brightness temperatures fall off considerably.

There is yet another kind of "temperature" with which we are concerned, namely the *effective temperature* of a star which is defined as the temperature of a black-body radiator for which the *total* energy emitted per unit area of surface, i. e. the energy integrated over *all* wave-lengths, is equal to the corresponding quantity for the star. Since all wave-lengths are not accessible to observation the effective temperature of a star is not an observable quantity; it appears as a parameter in theoretical work and a fully developed theory aims, *inter alia*, at the calculation of brightness and colour temperatures in terms of the effective. This reference to effective temperature marks the point at which we must leave our survey of the methods of observation and pass on to the second part of this address, in which I wish to attempt a brief description of the way in which progress has been achieved by interaction between observational work and the development of theory. If we want to understand what is happening in a star we have got to start from the observable data, which we may regard as being the visible symptoms of the underlying physical phenomena; like other sciences, astronomy has progressed by inductive enquiries in which hypotheses are set up, their consequences deduced, and then the deduced consequences are tested by fresh observation, the hypotheses then being modified if the new observations say that the predictions of the existing theory are incorrect, which happens very often. It is only in this way, and it can often be a very long way, that we can hope to arrive eventually at an understanding of what is happening, since some of the really important physical phenomena such as, for example, the temperature distribution with depth, which is one of the factors which governs the flow of energy through the outer layers of a star, are not themselves directly observable.

In attempting to review the work on spectral energy distribution which has taken place in the last 20 years, I propose to take up the story at a point subsequent to the classical researches of Lindblad (**5**), Milne (**6**), and Fowler and Milne (**7**), which stimulated observational activity. The position was briefly this: Lindblad and Milne had developed the theory of the radiative equilibrium of stellar atmospheres, the foundations of which had been previously laid by Schuster and Schwarzschild, and Milne, basing his researches on the hypothesis of radiative transfer, and on the hypothesis that the assumption of what is known as local thermodynamic equilibrium would provide a good approximation, had worked out the theory on the further assumption that the stellar absorption coefficient

* The relation between colour and brightness temperature at wave-length λ is

$$\phi_\lambda(T_c) = \left(1 + \frac{\lambda}{T_b}\frac{dT_b}{d\lambda}\right)\phi_\lambda(T_b),$$

where $\phi_\lambda(T)$ is the function of λ and T given above.

did not vary with wave-length in the outer layers of a star. He showed that this assumption, when added to the two fundamental hypotheses, led to calculated values for the Sun's centre-limb contrast which agreed well with the observational data then available and, furthermore, that it led to the conclusion that the stars radiated very much like black-bodies. This would mean that at all wave-lengths the colour and brightness temperatures should not differ much from the effective, and it also seemed that the effective temperature should roughly represent the actual average physical temperature in the reversing layer. With regard to the latter, Fowler and Milne had shown how the reversing layer temperatures could be inferred (on reasonable assumptions as regards the pressure) for the various spectral types from the observed maxima of the intensities of spectral lines. In short, the theory gave a definite set of temperatures, those of the Fowler-Milne scale, which were approximately identified with colour temperatures, and so were susceptible to observational test.

It was not very long before observation showed that something was quite seriously wrong. Measures of relative gradient difference between stars can be made comparatively easily, and with high accuracy, since the difficulties are absent which arise when the gradient difference between a star and a laboratory source has to be measured. Such measures of gradient difference were made at Greenwich, for the range of the visible spectrum, between stars of spectral types Bo to B3 and stars of spectral type Ao. The results obtained by my colleagues Davidson and Martin and myself (**8**) were definitely much smaller than the values calculated from the Fowler-Milne temperatures. Some years later, in 1934 (**9**), we completed the more difficult series of comparisons between stars and a standardized laboratory source, and we obtained for Ao stars a colour temperature of 18,000 deg. for a wave-length near λ 5000 as against the Fowler-Milne value of 10,000 deg., the discrepancy being too great to be possibly attributed to errors of measurement. It seemed as if it might be just possible to effect a reconciliation between theory and observation by postulating electron pressures about 100 times greater than those adopted by Fowler and Milne, but in the meanwhile Yü's study (**10**) of the Balmer discontinuity (the existence of which had been noted by Sir William and Lady Huggins (**11**) in 1899) had shown that for Ao stars the discontinuity was so great that the stars could not be regarded as being even approximately black-bodies. Attention had thus already been directed to the necessity of abandoning Milne's provisional assumption that the stellar absorption coefficient did not vary with wave-length, and an important advance had been made on the theoretical side.

This advance was made in 1931 by McCrea (**12**), who, using an approximation due to Eddington, calculated the emergent radiation for a model star composed entirely of atomic hydrogen. The importance of this work lies in the circumstance that hydrogen forms a very important constituent of stellar atmospheres, and a study of McCrea's model stars isolates one important contribution to the variation with wave-length of the stellar absorption coefficient. Between two consecutive series limits such as the Paschen limit at λ 8204 and the Balmer limit at λ 3646 the absorption coefficient of atomic hydrogen decreases with decreasing wave-length, but it is increased suddenly as we pass from the long wave-length side to the short wave-length side of each series limit. The slide (Fig. 1) shows one of the diagrams given in McCrea's paper in which the emission per angstrom per unit area of surface is plotted against wave-length for an atomic hydrogen

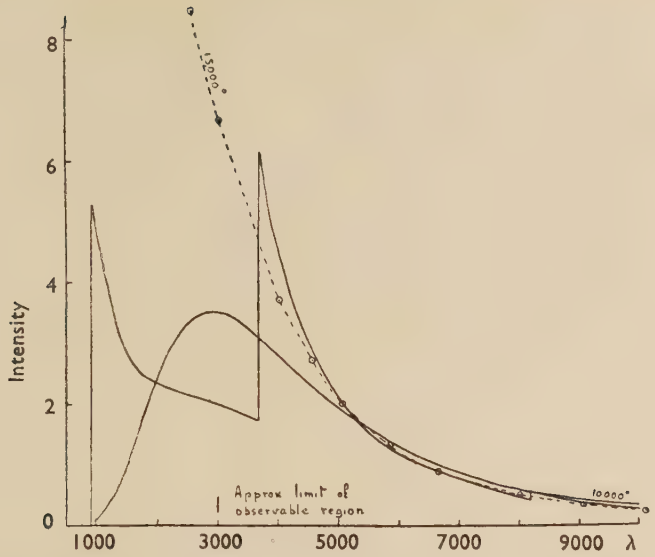

FIG. 1.—*Comparison of theoretical curves for hydrogen atmosphere* ($T_e = 10{,}000°$) *with black-body curves for* 10,000° (*absolute units*) $\left(\frac{10{,}000°}{\quad}\right)$ *and* 15,000° (*relative units*) $\left(\frac{15{,}000°}{\odot\text{---}\odot}\right)$.
[*McCrea, M.N.*, **91**, 855, *fig.* 10, 1931.]

star with effective temperature 10,000 deg. The corresponding curve for a black-body radiator at the same temperature is also shown. The areas between the two curves and the wave-length axis are of course the same, and represent the total energy output per unit area. The Balmer discontinuity is, as you see, about 3 to 1 for the ratio $I_{\lambda+}/I_{\lambda-}$ and is about equal to the measured value for A0 stars. The spectral energy distribution of the star does not bear any resemblance to a black-body distribution when all wave-lengths are considered, but on the redward side of λ 4500 the stellar distribution is an approximate fit to a Planck curve with $T = 15{,}000$ deg. plotted in terms of an arbitrary unit; that is, the colour temperature for wave-lengths greater than λ 4500 is roughly about 15,000 deg.; this value is actually in quite good agreement with the measured value for A0 stars, a circumstance of which McCrea was, at the time, unaware. The agreement of the stellar distribution, over a considerable spectral range, with a Planck curve for $T = 15{,}000$ deg. illustrates the warning previously given, that such a fit does not justify us in inferring that a star behaves like a black-body over the whole wave-length range.

McCrea's calculated models are for stars whose surface layers consist entirely of atomic hydrogen, and for real stars we have to consider other contributions to the total absorption coefficient. An attempt to take these into account was made by Pannekoek in 1936 (**13**). He considered a model stellar atmosphere composed of hydrogen and metals, the number of metallic atoms being 1/1000 of the whole. For the metals the representative composition advocated by Russell was adopted. The solar value of surface gravity was used. The computation of the various contributions to the absorption coefficient was made by an extension of Kramers' theory, and the emergent radiation was then calculated by an adaptation of Milne's analysis which incorporated the theorem of the Rosseland mean, a theorem which is really only true in the stellar interior but which has been considered to be a sufficiently good approximation for stellar

atmospheres. I show on the screen (Fig. 2) Pannekoek's theoretical energy distribution for an effective temperature of 10,080 deg. (surface temperature 8480 deg.) and you will see that the general trend of the calculated distribution is very similar to that shown on McCrea's diagram. For λ 5000 Pannekoek's calculated colour temperature is about 24,000 deg., which is greater than the measured value for A0 stars. There is an increase of colour temperature for the shorter wave-lengths on the redward side of the Balmer discontinuity. On the short wave-length side of the discontinuity the colour temperature is very much smaller. As in McCrea's diagram the calculations indicate an enormous discontinuity at the Lyman series limit (λ 911).

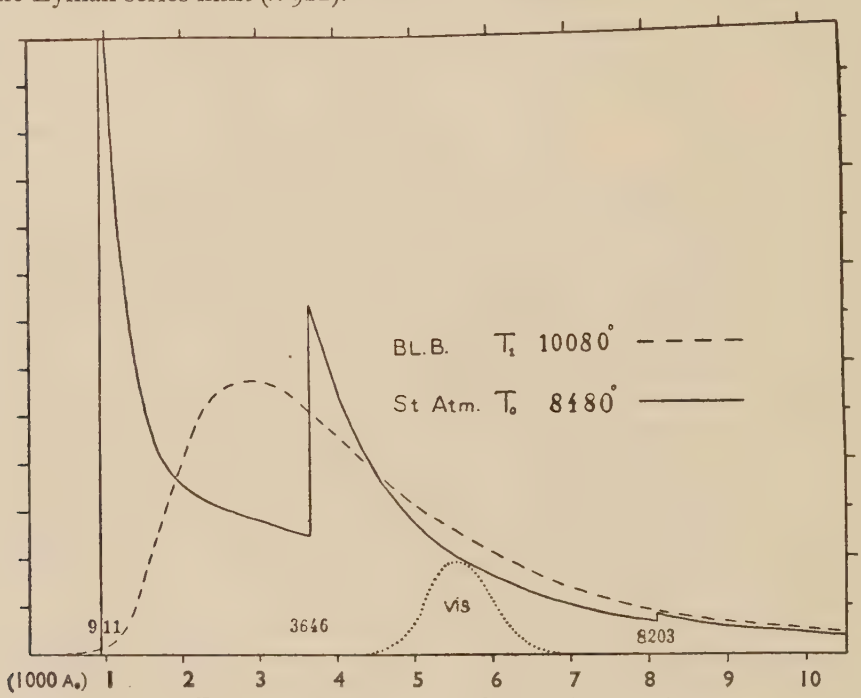

FIG. 2.—[*Pannekoek, Ap. J.*, **84**, 488, *fig.* 1, 1936.]

It is now time to return to observational progress. From 1934 to 1939 Barbier, Chalonge, and their collaborators (**3**) carried out a valuable series of measures at Jungfraujoch, using an ingenious slitless spectrograph and employing as their primary comparison source a hydrogen tube (developed by Chalonge and Lambrey) which gives a continuous spectrum of molecular hydrogen. They have obtained for 204 stars of all spectral types measures of the Balmer discontinuity and absolute gradients (values of ϕ_λ) for spectral ranges centred at λ 3500 and λ 4250. In addition to these and to the Greenwich measures, which refer to λ 5200, we also have absolute gradients measured by Kienle and his colleagues at Göttingen (**14**), (**15**) for two spectral ranges centred at λ 5700 and λ 4400, and measures at Ann Arbor by R. C. Williams (**16**) referring to λ 5000. Within the permissible limits of observational error these series of measures seem to be accordant in indicating a value of 1·1 for ϕ_λ at λ 5000 for main sequence A0 stars, the corresponding colour temperature being 15,500 deg. According to the Göttingen measures ϕ_λ decreases substantially from λ 5700 to λ 4400, corresponding to an increase in colour temperature, but this is not confirmed by the Ann Arbor results. On the short wave-length side of the Balmer discontinuity the

colour temperature is much smaller, the value of ϕ_λ at $\lambda 3500$ being 1·4, corresponding to $T_c = 10{,}500$ deg. The measured value of the Balmer discontinuity for these stars has already been mentioned; it is $D = 0{\cdot}47$, corresponding to a light ratio of about 3 to 1, a result which is in good agreement with the discontinuities calculated by McCrea and Pannekoek. For the normal Bo stars the combined observational results indicate $\phi_\lambda = 0{\cdot}9$ at λ 5000, corresponding to $T_c = 22{,}000$ deg. For this spectral type there is no longer a marked drop in colour temperature on the short wave-length side of the Balmer discontinuity; the value of ϕ_λ at λ 3500 is 0·8, corresponding to $T_c = 21{,}000$ deg. The discontinuity is small for the normal Bo stars, the measured value being $D = 0{\cdot}04$.

The considerable decrease in colour temperature which is found for Ao stars on passing from the long wave-length side to the short wave-length side of the Balmer discontinuity, appears to be a fact of some significance. I have already mentioned the two fundamental hypotheses which have formed the basis of theoretical investigations on the continuous spectrum up to the present time. In the theory there are two main steps, firstly the calculation of the temperature distribution with depth, and secondly the calculation of the outflow of radiant energy from the surface. The calculation of the temperature distribution involves both of the hypotheses, namely, (1) the hypothesis that radiation is the only mechanism whereby energy is transferred outwards from the interior, and (2) the hypothesis of local thermodynamic equilibrium, which states that the ratio of emission to absorption coefficient at any depth is the same as for matter in full thermodynamic equilibrium at the corresponding temperature. But once the temperature distribution with depth has been found the subsequent calculation of the emergent radiant flux at any wave-length involves the second hypothesis alone. Now there is one particular case in which a result can be obtained for the emergent flux, i. e. for the brightness temperature, in the absence of any knowledge of the temperature distribution, so that the calculated result depends only on the one hypothesis of local thermodynamic equilibrium. This is the case in which over a limited spectral range the absorption coefficient is very much greater than the average; the actual mathematical case is that of infinite absorption coefficient over a limited spectral range, and, under such circumstances, if we assume that local thermodynamic equilibrium holds good right up to the surface, then it follows that throughout the spectral range in question the colour and brightness temperatures are equal and are independent of the angle of emergence, each being equal to the physical temperature at the surface. This is a result for the limiting case of infinite absorption coefficient over a prescribed spectral range. For a spectral range over which the absorption coefficient is very much larger than the average, we may expect an approximation to this limiting case, so that the colour and brightness temperatures would approximate to the surface temperature. Such a spectral range with large absorption coefficient will be found immediately to the short wave-length side of any large hydrogen discontinuity, since a large discontinuity is the result of a large increase of absorption coefficient as we pass to the short wave-length side. Now for main sequence Ao stars the Balmer discontinuity is large, the ratio $I_{\lambda+}/I_{\lambda-}$ being about 3 to 1, and it is at once suggested that the low colour temperature of 10,500 deg. at λ 3500 for these stars is a good approximation to the surface temperature and, further, that the colour and brightness temperatures in this spectral region should be independent of the angle of emergence, there being no variation from centre of disk to limb, so that the colour temperature

of an eclipsing binary should be the same for all phases. This is a conclusion which can be checked by observation; the Jungfraujoch observations of Algol (spectral type B8) do in fact show that at λ 3500 the change in colour temperature with phase is much less than for λ 4250, and Barbier and Chalonge consider that the change at λ 3500 is so small as to constitute a verification of the hypothesis of local thermodynamic equilibrium. If this be substantiated by further measures it is an important result, and indeed the facts as known at present would seem to justify the conclusion that this hypothesis is substantially correct and will not have to be discarded, although of course the possibility of minor modification cannot be excluded. If the hypothesis be accepted, then it would follow that the measured colour temperatures at λ 3500 would be good approximations to the surface temperatures for stars whose Balmer discontinuities are sufficiently large, and, since the Algol measures indicate that this state of affairs is being approached for this particular star, it seems that the approximation should be a good one for stars whose discontinuities exceed that of Algol. The measured value of the discontinuity for Algol (uneclipsed) is $D = 0{\cdot}31$, and for A0 stars we have $D = 0{\cdot}47$, so we would seem to be justified in regarding the colour temperatures at λ 3500 for the main sequence A0 stars as good approximations to the surface temperatures. It is this circumstance, connected, as we have just seen, with the large values of the Balmer discontinuity, which makes A0 stars of special interest.

I shall now have to review very briefly indeed the theoretical developments of the last ten years. In the first place the actual mathematical technique of calculating the emergent radiation, given the variation of absorption coefficient with wave-length, has been refined, a process in which Chandrasekhar has played a prominent part in a remarkable series of papers which have appeared in the *Astrophysical Journal* from 1944 onwards. The errors introduced by certain approximations in the earlier work have been removed, and as an example of this I show a diagram (Fig. 3) given by Barbier (**17**) which shows the effect of

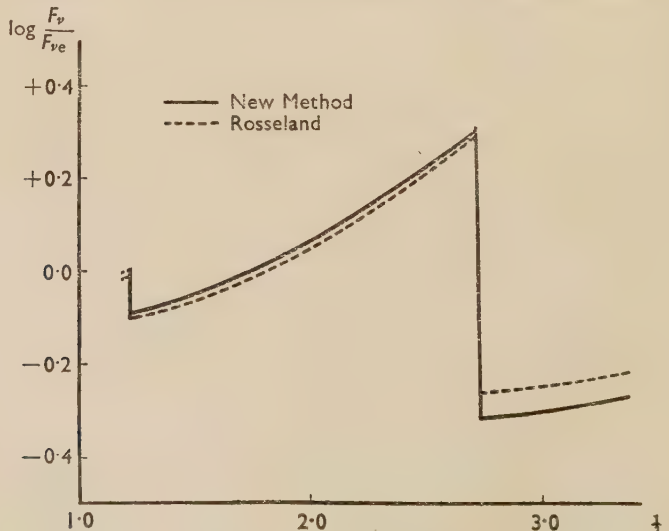

FIG. 3.—*A0 stars. Total flux.*
Full curve: new calculation.
Broken curve: calculation employing the Rosseland mean.
[*Barbier, Annales d'Astrophysique*, **6**, 128, *fig.* 5, 1943.]

correcting the error introduced by using the approximation of the Rosseland mean. Apart from these improvements in the mathematical analysis the only new physical process which has been considered, since McCrea's paper drew attention to the important part played by atomic hydrogen, is the contribution to the absorption coefficient made by negative hydrogen ions, each consisting of a proton and two electrons, to the astrophysical importance of which attention was directed by Wildt (**18**). In a recent paper Chandrasekhar and Münch (**19**) have shown that if we consider stellar models of hydrogen alone, the calculated combined absorption coefficient of H and H^- leads to colour temperatures and Balmer discontinuities in good agreement with the observed results for stars of the main sequence of spectral types Ao to Go. From this it would appear that the contributions made by the metals to the total absorption may be negligible in the first approximation; if this be so, it is a fortunate circumstance, since the theoretical calculation of metallic absorption coefficients is still a matter subject to considerable uncertainty. The earlier calculations are open to grave suspicions; more recent research does not support the validity of the extension of the Kramers theory to other than hydrogen and hydrogenic * atoms.

For stars of spectral type earlier than Ao there are some unexplained discrepancies, but the general tendency of late has been for the refined theory to give results in agreement with observation. There does not seem, so far, to be any grounds for anything like a drastic reconstruction of the two fundamental hypotheses. We have, as I have remarked, found some reason for believing, whilst admitting the possibility of minor modification, that the hypothesis of local thermodynamic equilibrium is substantially correct, at any rate up to a level close to the visible surface. With regard to the hypothesis of radiative transfer, it would probably be wise to defer judgment until more exhaustive comparisons of theory and observation have been effected. In addition to the measurements which have been made, measurements in the near infra-red should before long extend our knowledge, and for the Sun we are beginning to have data for the far infra-red, which indicate very high brightness temperatures, of the order of 10^6, for wave-lengths of the order of one metre. The Sun also provides a further means of checking theory, since measures of brightness and colour temperature can be made at varying distances from the centre of the disk, i.e. for varying angles of emergence of the radiation. As regards the far ultra-violet, the output of short-wave solar radiation stimulates other observable effects such as cometary and ionospheric phenomena, and we may get valuable data in this way; similarly we may get information about the output of energy in the far ultra-violet for early type stars, since this radiation is responsible for stimulating nebular emission. It may well be that as a result of extensive tests we shall have to modify our hypotheses, and there are already some considerations—I fear I cannot discuss them to-day—which have given rise to the suspicion that convective transfer may play a material part in determining the temperature distribution with depth. But for the present I think that they remain suspicions, and that so far, at any rate as far as observations of the continuous spectrum are concerned, there seems to be no really valid reason for a substantial modification, at this stage, of our two hypotheses. It seems to me that we should not attempt any such reconstruction of our ideas until the existing theory has been shown to be definitely incompatible with observation. This is, of course, merely a personal opinion.

* i. e. He^+, Li^{++} and other atoms consisting of a nucleus and a single electron.

I now turn to another field of work and I propose, in the concluding part of this address, to attempt a brief survey of the problem presented by abnormally coloured stars of early spectral type. This group of stars, to which attention was first directed by Hertzsprung (**20**) in 1923, are characterized by colour temperatures which are very much smaller than the normal values for their types. A typical example is 55 Cygni, whose spectral type is B2 but whose colour, in the visible region of the spectrum, is roughly the same as that of the Sun. For some time astronomers have been accustomed to attribute the abnormal colours of these stars to the reddening effect of selective scattering by obscuring matter in interstellar space, and, in fact, it seems quite certain that such an effect is operative, as has been shown, for example, by the researches of Zug (**21**) on galactic clusters and of Stebbins and Whitford (**22**) on globular clusters. But there has been some evidence which seems to indicate that this may not be the whole explanation. In 1934, E. G. Williams (**2**) published a detailed examination of the relation between colour excess (i. e. the excess of the colour index of a star over the normal value for its spectral type) and the intensity of the interstellar K line, which may be regarded as a rough measure of distance. He gave a diagram, which is reproduced below (Fig. 4); the abscissae are measures

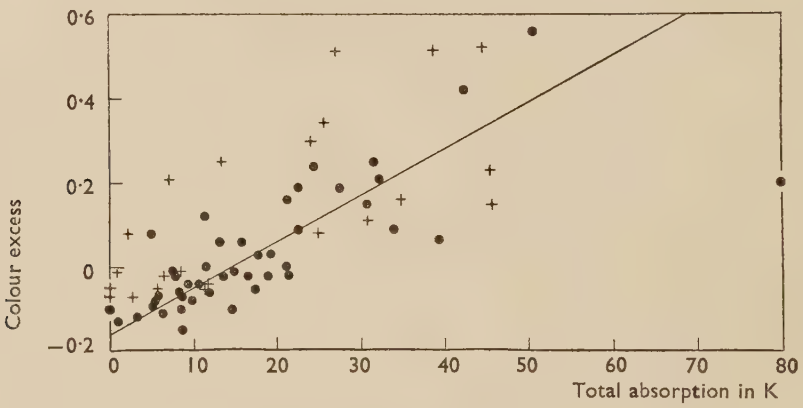

Fig. 4.—*Colour excess (ordinates) and total absorption in the interstellar K line. The crosses represent bright-line stars.*

[*E. G. Williams, Ap. J.*, **79**, 299, *fig.* 7, 1934.]

of the total absorption of the K line and the ordinates are colour excesses obtained from photoelectric magnitudes, these magnitudes being first corrected for line absorption (or emission) so as to make them applicable to the continuous spectrum alone (I have already referred to the corrections which were obtained by Williams for this purpose). You will see that (apart from one star, H.D. 212455, spectral type B3, which has a strong K line but is not reddened to a corresponding extent) there is a general correlation between colour excess and K-intensity, as we should expect if the reddening is due to scattering by interstellar material. But the stars with *e* characteristic, i. e. the stars characterized by emission spectral lines, seem to be too red for their distance; they appear as crosses on the diagram, and Williams pointed out that these crosses, on the whole, are above the line of regression drawn through the representative points for the other stars, indicating that the *e* stars are more reddened than other stars at the same distance. There is a definite suggestion that in addition to reddening by interstellar material the *e* stars are affected by a reddening process which is intrinsic to the stars themselves.

The suspicion that some such process is operative is enhanced by the behaviour of γ Cassiopeiae, which during the period 1936 to 1938 reddened and, as was shown by colour temperature measures made at Greenwich (**23**) in the visible spectral range, temporarily joined the ranks of what have been described as the "yellow" stars of early type, i.e. the abnormally coloured stars we are now considering. The reddening of γ Cassiopeiae at this period was accompanied by the development of emission lines and is clearly due to some process intrinsic to the star itself.

The publications in 1940 (**24**) of the Greenwich list of relative gradients for 250 stars, which refer to the (harmonic) mean wave-length λ 5100, and in 1941 (**3**) of the two Jungfraujoch series for λ 4250 and λ 3500, have given material for a more detailed examination of the reddening effect. For each series we can subtract the gradient appropriate to the type, as given by the measures for normal stars, from the gradient for a "yellow" star, thus obtaining "gradient excesses" which are analogous to colour excesses but which refer to the continuous spectrum alone. This is an important characteristic of gradient excesses in view of the circumstance that the "yellow" stars of early type show a marked tendency to exhibit the *c* or *e* characteristics or both, so that the contributions made by spectral lines to heterochromatic magnitudes would tend to be different for such stars as against normal stars. On examining the material, the first and most striking conclusion, which is apparent on a mere casual inspection of the results, is that the gradient excess, which is a measure of the reddening effect, is much smaller for the shorter wave-lengths. Apart from γ Cassiopeiae, to which I shall return shortly, this effect is present in all the other 14 stars of spectral types B0 to B2 which are common to the Jungfraujoch and Greenwich lists and which are heavily or moderately reddened. I shall quote some examples. Measured relatively to the mean of β Cephei and ϵ Persei, which are two normal stars of type B1, the gradient excesses of P Cygni, a "yellow" *e* star of the same spectral type, are 1·29 for λ 5100, 0·93 for λ 4250 and 0·43 for λ 3500. For χ^2 Orionis, type B2*ce*, the gradient excesses relative to the mean of γ Orionis and γ Pegasi are 1·04 at λ 5100, 0·54 at λ 4250 and 0·31 at λ 3500. For 9 Cephei, type B2*c*, the corresponding excesses are 0·97, 0·78 and 0·61; and so on. The decreases of the excesses for the shorter wave-lengths are large. In their discussion, published in 1941, of the Jungfraujoch material, Barbier and Chalonge apparently did not have access to the complete list of Greenwich gradients published in the *Monthly Notices* for January 1940, and they were only able to compare their results with the much less extensive Greenwich material published in 1932. Nevertheless, they were able to call attention to a few examples of this progression of gradient excess with wave-length. Their study of ζ Persei, spectral type B1*c*, is of particular interest, since in addition to the Jungfraujoch and Greenwich measures there were available gradients for λ 5700 and λ 4400 measured at Göttingen (**14**), and gradients for λ 8000 and λ 5700 deduced by Barbier and Chalonge from Hall's measures (**25**), made at the Sproul Observatory, of the differences of magnitude between this star and ϵ Persei. The slide (Fig. 5) shows their diagram for the gradient excess of ζ Persei relative to ϵ Persei plotted against reciprocal of wave-length. Barbier and Chalonge seem inclined to challenge the value at λ 8000 deduced from Hall's measures. I do not think that anyone who studies Hall's paper carefully will feel that the permissible accidental errors of observation could seriously affect the position of this point

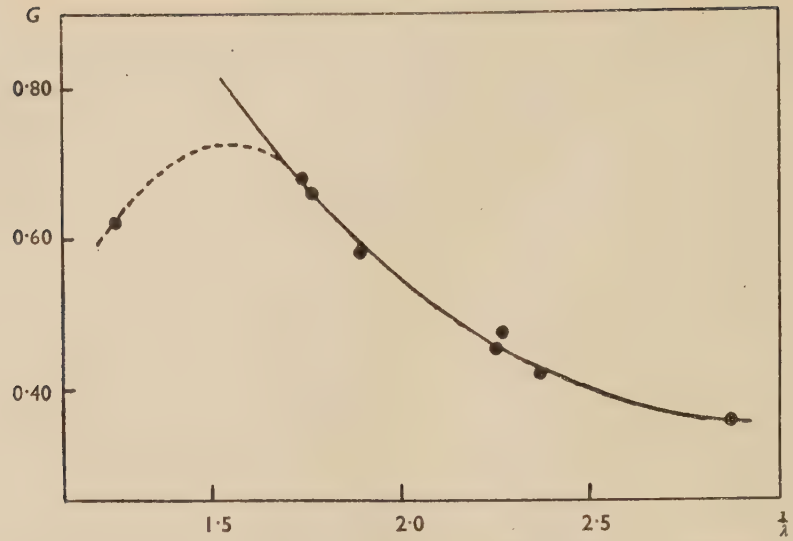

FIG. 5.—*The gradient excess of ζ Persei relative to ε Persei plotted as a function of 1/λ. λ=wave-length in microns.*

[*Barbier and Chalonge, Annales d'Astrophysique*, **4**, 88, *fig.* 25, 1941.]

on the diagram, but there is a question as to whether Hall's infra-red results do really appertain to the continuous spectrum, since his magnitudes refer to spectral ranges which are usually 980 A. wide (the measures are photoelectric measures of the total light in blocks of wave-length isolated by the use of a coarse slit and a wire grating of low dispersion). The measures in the infra-red would certainly be affected by the Paschen lines of hydrogen, which, if the Balmer lines are any guide, would be stronger for ε Persei than for ζ Persei. But it is impossible, in default of a proper spectrophotometric investigation of the Paschen line strengths, to estimate the corrections necessary to reduce the measures to the continuous. If the infra-red gradient excess as shown is anything like right, it means that the gradient excess, i. e. the reddening effect, reaches a maximum somewhere towards the red end of the visible spectrum. If this is really so, it is an important result, and the doubt that arises with regard to it emphasizes the need for spectrophotometric measures of relative gradient in the near infra-red, the continuous being properly isolated. Apart from the infra-red point the diagram shows the progressive decrease of gradient excess for diminishing wave-lengths.

A curve of this kind exhibits the gradient excess as a function of wave-length, and if the reddening be ascribed wholly to scattering by interstellar material we can get the variation of the obscuration with wave-length by integration, since the gradient excess is 0·921 times the derivative of the obscuration in magnitudes. A constant of integration is, of course, introduced. I show on the screen (Fig. 6) curves given by Barbier and Chalonge which were obtained by integrating the gradient-excess curves. The curves are for ζ Persei, χ^2 Orionis and 9 Cephei, the constants of integration being adjusted so as to make the curves intersect at λ 4000. The ordinates represent obscurations in magnitudes multiplied by the factor 0·921, and you see that the obscurations increase towards the ultra-violet, but at a decreasing rate with regard to the reciprocal of wave-length, this decreasing rate corresponding to the decrease of gradient excess.

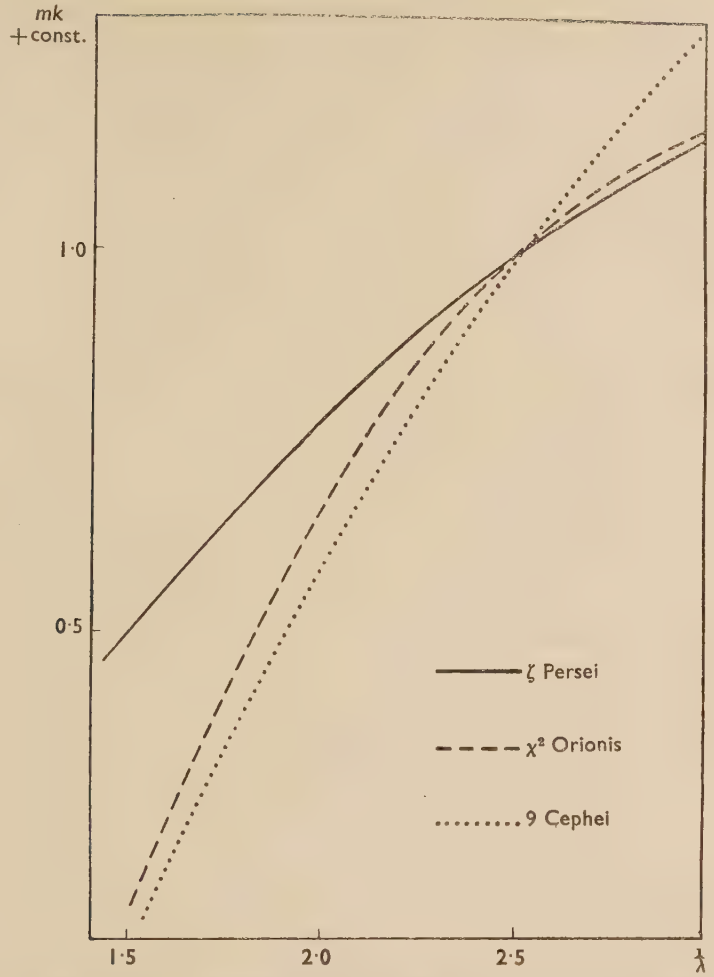

FIG. 6.—*Abscissa* $= 1/\lambda$. *Ordinate* $=$ mk $+$ *const where* m *is the total mass of obscuring matter in a beam of unit cross-section and* k *is the obscuration coefficient* (*so that* mk $= 0{\cdot}921 \times$ *obscuration in magnitudes*).

[*Barbier and Chalonge, Annales d'Astrophysique*, **4**, 91, *fig.* 27, 1941.]

Numerical analysis of the results shows that the variation of obscuration coefficient with wave-length is different for these three stars, and Barbier and Chalonge consider that the differences are to be ascribed to variations in the nature and dimensions of the scattering particles in different regions of the Galactic System.

The results for γ Cassiopeiae, at the period when it could be considered to be one of the group of "yellow" stars of early type, are different. From the measures made at Greenwich and Jungfraujoch in 1936 and 1938, we find that, as for other reddened stars, the gradient excess at λ 4250 is less than at λ 5100, but that at λ 3500 the gradient excess is greater than at λ 4250. The diagram on the screen (Fig. 7) shows the interpretation given by Barbier and Chalonge, who consider that there is a discontinuity in the gradient excess at the wave-length of the Balmer discontinuity. This is a plausible suggestion in view of the fact that during this period, when γ Cassiopeiae was reddened, the Balmer discontinuity was negative, i.e. the continuous spectrum was more intense

on the short wave-length side, the normal continuous Balmer absorption being replaced by continuous Balmer emission. Barbier and Chalonge suggest that this type of reddening, with a discontinuity in the gradient excess, is characteristic of all reddened early type *e* stars. But from the more extensive material, not

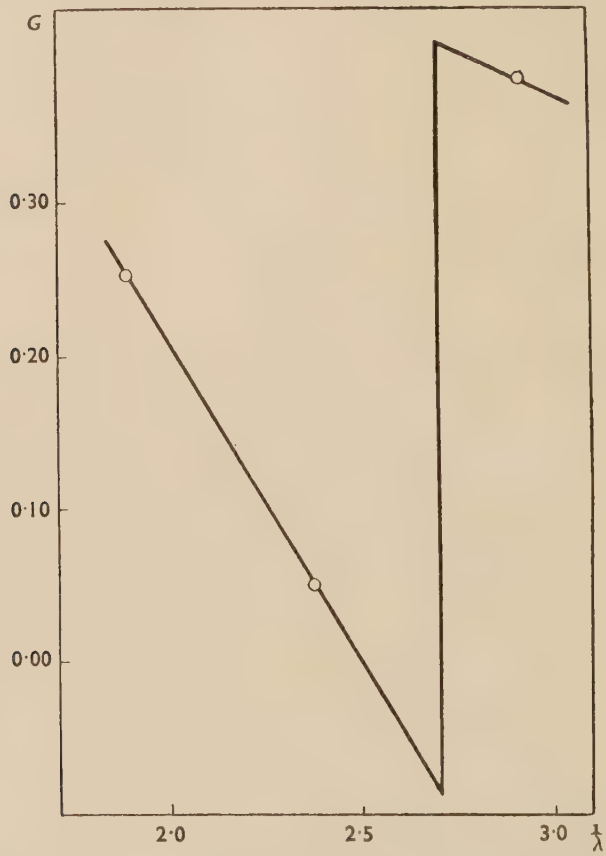

FIG. 7.—*The gradient excess of γ Cassiopeiae (in 1938 when the emission spectrum was a maximum) relative to ε Persei plotted as a function of 1/λ.*
[*Barbier and Chalonge, Annales d'Astrophysique,* **4**, 83, *fig.* 22, 1941.]

available to them at the time, it does not appear that among the stars of spectral types B0 to B2 the emission stars are especially distinguished as far as the variation of gradient excess with wave-length is concerned. However, it still remains possible that what may be called the γ Cassiopeiae type of reddening is affecting other reddened stars of early spectral type to some extent, and that it represents a type of reddening which is intrinsic to the stars themselves and which is additive to the reddening by interstellar material. It would be possible to ascribe to this type of reddening the variations between the extinction curves for different stars which were attributed by Barbier and Chalonge to variations in the nature of the obscuring material in different parts of the Galaxy. But this, of course, would be mere speculation in the present state of our knowledge.

The comparison of the full Greenwich material with the Jungfraujoch gradients reveals some facts relating to the stars of type O which attract our attention. From the measures at λ 4250 and at λ 3500 we find that as we pass from type A0

through type B to type O*e*5, the colour temperature of the bluest stars of each spectral type, i. e. of the stars which have been regarded as "normal", increases progressively. But for the same stars the colour temperature at λ 5100 seems to come to a maximum value at about spectral type B2 and then to decrease again, the colour temperature at λ 5100 for O*e*5 being lower than for B2. This suggests that the reddening effect is operative for even the bluest stars of type O*e*5. The next fact is that the material includes two O*e*5 stars, 68 Cygni and ξ Persei, which are definitely reddened, and that the reddening, measured relatively to the bluest stars of the same type, does not seem to conform to the progression with wave-length found for the type B stars, the gradient excesses of these two O*e*5 stars being more for λ 4250 than for either λ 3500 or for λ 5100. This is especially marked in the case of ξ Persei, the gradient excesses (relative to the mean of 10 Lacertae, 15S Monocerotis and λ Orionis) being 0·36 at λ 5100, 0·62 at λ 4250 and 0·18 at λ 3500. Of course we can restore the progression with wave-length by assuming that the bluest stars of this spectral type are themselves reddened, and so measuring our gradient excesses relatively to a hypothetical O*e*5 star bluer than the bluest star of the type. But this will not ease the difficulty that we meet if we insist on assuming that the reddening is entirely due to interstellar scattering. If the scattering material be considered to be homogeneous, then the gradient excesses for the yellower stars of this type, measured relatively to the bluer stars, must represent the scattering effect of the excess material traversed by the light from the yellower stars, and we should accordingly expect the same progression of reddening effect with wave-length as we get for stars of type B. The hypothesis that interstellar scattering is the only operative cause will thus lead us to the same conclusion as that reached by Barbier and Chalonge, that the scattering material is not homogeneous; and we should have to regard the behaviour of O*e*5 stars like ξ Persei as much more pronounced cases of the variations to which Barbier and Chalonge drew attention. It may be that it will prove to be difficult, and perhaps impossible, to develop a theory of scattering capable of explaining the measures for stars like ξ Persei and ζ Persei, for which the variations of gradient excess with respect to wave-length are very different.

The third interesting fact about the O*e*5 stars is that the intensities of the interstellar K and D lines for the two reddened stars are about the same as the mean intensities for the bluer stars (and are definitely less than the intensities for λ Orionis, which is one of the bluer stars). If we insist on the hypothesis of pure space reddening this will lead to the conclusion that the distributions in space of the reddening material and of the *Na* and Ca^+ atoms which produce the interstellar lines are quite different.

It is impossible to sum up the existing evidence without expressing a personal opinion. If I may be allowed to do this on the present occasion, I get the feeling that although the existence of intrinsic reddening in addition to space reddening has not been established beyond all doubt, the balance of evidence favours the idea that reddening by interstellar scattering is not the only process involved. It seems to me that difficulties are going to arise as soon as we try to develop a detailed theory of scattering which will explain all the phenomena, and I am inclined to suspect that these difficulties may prove to be unsurmountable. We may well be forced, as a result of a developed theory of scattering, to ascribe some of the reddening to some effect intrinsic to the stars, involving possibly a

departure, for such stars, from Milne's fundamental hypothesis of local thermodynamic equilibrium. But one thing does seem to be very clear, and that is that we do not yet know enough of the observable facts, and that further measures are very desirable before we begin to attempt the task of interpretation. In particular we need to study the variation of gradient excess with wave-length in much greater detail, and to do this we need well determined relative gradients for wave-length ranges which, when combined, will cover the whole field from the near infra-red to the near ultra-violet. Since we only want to know the relative gradients (and the relative values for the Paschen and Balmer discontinuities) between the reddened stars and the so-called normal stars of the same spectral types, the necessary measures can be restricted to purely relative work, there being no need to obtain comparisons between stars and a standardized laboratory source of light, a process which inevitably introduces larger errors than those appertaining to the measures of relative gradient between star and star. Relative gradients can be measured with high accuracy; for the Greenwich measures the probable error is $\pm 0{\cdot}02$ for the mean of four determinations, and this in spite of the circumstance that the atmospheric conditions at Greenwich were none of the best. A point has now been reached at which the material secured so far can be regarded as being in the nature of a preliminary survey which has identified objects of special interest, and which thus enables us to concentrate future activity on such objects. The road is now open for anyone possessing the necessary equipment to make a substantial contribution to knowledge within a reasonable time by obtaining data which will provide a reliable basis for the difficult task of interpretation.

I have confined myself in this address to a survey of two main lines of research in the study of the continuous spectrum. I have not been able to survey the whole field and I particularly regret that the centre-limb contrasts for the Sun have received only a passing mention. It is with some difficulty that I have resisted the temptation to refer to the continuous spectra of solar flares. We know next to nothing about the continuous spectra of flares, and it is accordingly a subject which invites speculation, since temptation to speculation is apt to vary inversely with extent of knowledge. But I hope I have said enough to bring out the fact that the study of the continuous spectrum is a live subject which is full of interest. It is a subject in which we are apt to get surprises; in the past the observational material has given some rude shocks to existing conceptions, and I don't think that that happy state of affairs has come to an end yet. It is very probable that further surprises are in store. The study of the continuous spectrum can thus, I think, be fairly said to be very much alive and kicking.

1948 March. My thanks are due to the authors and periodicals concerned for permission to reproduce as diagrams the seven slides shown. I am also indebted to Dr E. A. Baker who has redrawn these diagrams for publication.

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